SPACE PROCESSING APPLICATIONS PAYLOAD EQUIPMENT STUDY

VOL. IID. SPA SUPPLEMENTAL POWER AND HEAT REJECTION KIT

DPD NO. 40
DR NO. MA-04
DCN NO. 1-3-21-00235
CONTRACT NO. NAS 8-28938

JULY 1974

R. L. HAMMEL
A. G. SMITH
(EDITORS)

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

BY

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SYSTEMS GROUP

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SPA SUPPLEMENTAL POWER AND HEAT REJECTION KIT

1. SUMMARY

Since both the power availability and heat-rejection/thermal control capability of the Spacelab were found to be insufficient to fulfill the experiment requirements of the Space Processing discipline, it was decided to utilize a supplementary power and heat rejection kit (PHRK). This kit will be supplied by the SPA payload and will be used in conjunction either with manned experiments in the Spacelab's experiment module, with unmanned experiments in the Spacelab's cargo bay, or wit. a combination of these. The PHRK will be located in the cargo bay for all three of these mission modes.

The two subsystems of electric power and thermal control were analyzed in order to define the requirements for the SPA PHRK.

As a basis for the analyses, twelve exemplary experiments were defined and power timelines were developed. From these timelines, the experiment requirements for sustained power, peak power and energy were determined. The power and energy requirements at the power source were extrapolated by using these raw figures and estimations of line losses, efficiencies and contingency factors.

The current Spacelab subsystem requirements were estimated to result in a payload power allocation from the shuttle of 4.0-4.8 KW average and 9.0 KW peak for 15 minutes. The PHRK will provide up to 14 KW continuous average power and peaks up to 24 KW for 15 minutes. The use of both power sources will allow from 4.0 KW to 18.8 KW of continuous average power to the experiments along with peak powers up to 33 KW for 15 minutes. This utilization mode will accommodate all of the twelve exemplary experiments, whereas use of shuttle power alone will not.

The electrical power subsystem of the PHRK will be comprised of two fuel cells, oxygen and hydrogen reactant tank assemblies, water storage tanks, plumbing, cabling and inverters to convert the nominal 28 VDC fuel cell output to AC power. The reactant tank assemblies will provide for sufficient cryogenic storage of hydrogen and oxygen to provide about 1000 KWH of energy.

The electrical power distribution subsystem will provide the interface between the power source and the experimental equipment. It will provide the functions of power switching/distribution, signal conditioning/distribution and interconnection of all electrical interfaces. The baseline power distribution system is an AC system that utilizes 115 VAC - 400 Hz, single-phase inverters for low power and 115 VAC - 1600/1800 Hz, three-phase, four-wire inverters for high level power. Power conversion will be provided by static DC to AC inverters.

The thermal control subsystem (TCS) must maintain the environment of the experiment modules and payload equipment. The TCS of the PHRK will consist of a pumped liquid loop which rejects thermal energy to space via thermal radiators located on the exterior of the PHRK structure. There will be two radiators -- the high temperature, primary radiator for high heat rejection and the secondary radiator to provide a temperature drop for the electronic equipment operating at room temperature (approximately ten percent). Thermal capacitors, assumed to be stearic acid, will be included in the system downstream of the primary radiator to store thermal energy that exceeds the radiator's capacity. At an appropriate time it can be removed from the capacitor and rejected to space via the radiator.

Weight and volume estimates were prepared for the automated experiment package and weight estimates for the PHRK. The complete system will require a weight allocation of 4354 kg (9605 lb) an austere version will require only 2560 kg (5645 lb). Six different configuration layouts were prepared for the PHRK using these figures. Also, three drawings were prepared showing the PHRK schematic, a modular kit and the structural configuration used in the loads analysis. This analysis was performed to define the structural weights needed to accommodate the weights and volumes of the PHRK and the experimental equipment. The results of this analysis are included in the Appendix.

2. INTRODUCTION

NASA Contract NAS 8-28938 defined a set of modular, reusable and reconfigurable equipment payload subelements needed to perform research and development in the area of processing of materials in space. These subelements require certain resources from the Spacelab and likewise impose certain interface requirements upon it. The subsystems of power conditioning, power distribution, thermal control and heat rejection were amongst those chosen for study regarding the feasibility of the payload equipment, host vehicle interfaces, possible alternatives and accommodation concepts.

An examination of the power requirements to perform exemplary SPA experiments revealed the need of greater power levels and energy resources than that available from Spacelab. Likewise, this increased power usage and energy consumption presents a problem in the area of thermal control and heat rejection. Both of these areas will be discussed in Section 3.0.

Since it has been determined that it will be necessary to supply a supplemental power and heat rejection kit, several different packaging concepts were examined. These six concepts are briefly summarized in Section 4.0.

The preliminary design for the Power-Heat Rejection Kit proceeded on the following assumptions:

1. An allocation for weight and volume of experimental gear was to be established.
2. Placement of experiment subelements within the structure was to be based upon:
   - feasibility of providing thermal control,
   - ability to integrate/reconfigure,
   - maintaining Cg control (axial/radial).
3. Structural design support was to be developed. Other subsystems treatment of the automated payloads proceeded on the basis of assuming that they have characteristics identical to the internal Spacelab SPA subelements.

4. Baseline Shuttle system documentation is as listed below and is available.

Space Shuttle and Spacelab Discussions
October 11-12, 1973

Vol. A -- Structures Thermal, and Mechanical Systems	SL-6.3.1.1
Vol. A, App. A -- Payload Accommodations Baseline Drawings	SL-6.3.1.1
Vol. B -- Envir. Thermal Control and Life Support Systems	SL-6.3.1.2
Vol. C -- Avionics	SL-6.3.1.3
Vol. E -- Mission Operations	SL-6.3.1.5
Vol. F -- Shuttle/Payload Safety	SL-6.3.1.6
Vol. G -- Contamination Overview	SL-6.3.1.7

5. Heat rejection capacity was to be based upon handling only that amount which the supplemental power embodies. We assumed Spacelab will handle the baseline values.

From the six concepts, one was chosen for further analysis (Configuration 3) to ascertain the accommodation which might be provided. This configuration was analyzed with the assumption that an automated SPA payload consisting of furnace, levitation and core subelements would also be contained in the Kit. Weight summaries, structural sizing calculations and detailed layouts for the Kit are included in Section 5.0.

3. SUBSYSTEM ANALYSIS RESULTS

3.1 ELECTRICAL POWER SUBSYSTEM

3.1.1 Key Study Interface Activities/Guidelines

The major concerns of the electrical power subsystem have been to review and evaluate the electrical power demands of exemplary space processing experiments as they relate to total power availability and capability, total energy demand and the evaluation of supplemental power sources.

3.1.1.1 Power Requirements

The number of possible SPA experiments are many. For the purpose of this analysis the equipment and load profiles for twelve representative experiments have been identified. These are listed in Table 1 along with a brief word description of each experiment. In this report the twelve experiments will subsequently be identified by the numbers one through twelve as indicated.

3.1.1.2 Power Availability

The Shuttle Orbiter provides electrical power from its three fuel cells to support the Orbiter and the Spacelab operations. One of the three Shuttle Orbiter fuel cells is dedicated to the Spacelab electrical power requirements during normal Shuttle operation. Each fuel cell has a capability of providing from 2.0 to 7.0 KW continuously with peak capability of up to 12.0 KW for 15 minutes. This power supplies the Spacelab subsystems and the excess is available to the payload. A summary of these capabilities and their characteristics are shown in Table 2. The normal energy available from the Orbiter is 50 KW-hours, however, an additional 900 KW-hours can be provided by the Orbiter if the reactant and tankage weights are charged to the Spacelab or the experiments.

The current Spacelab subsystem requirements were estimated to result in a payload allocation of 4.0 to 4.8 KW average and 9.0 KW peak. The average power is a 24 hour/day average and the peak is a 15 minute maximum duration peak with a minimum separation of 3 hours between peaks.

Table 1. SPA Experiment Identification

No.	Exemplary SPA Experiment Class	R&D Category	Subelement
1.	Encapsulated Immiscible Combination	Metallurgical	Furnace
2.	Preparation of Pure Alloys - Containerless Melting	Metallurgical	Levitation
3.	Molten Zone Crystal Growth	Crystal Growth	Furnace
4.	Crystal Growth by Pulling from a Containerless Melt	Crystal Growth	Levitation
5.	Preparation of Multiphase, Silicate-Based Glass	Glass Technology	Furnace
6.	Containerless Preparation of La_2O_3-Based Glass	Glass Technology	Levitation
7.	Stationary Column Electrophoretic Separation of Proteins	Biology Applications	Biological
8.	Continuous Flow Electrophoretic Separation of Proteins	Biology Applications	Biological
9.	Containerless Position Control of Liquids by Electromagnetics	Physical Processes in Fluids	Levitation
10.	Thermal Gradient Convection in Liquids	Physical Processes in Fluids	General
11.	Chain Reactions Affected by Convection	Chemical Processes in Fluids	Levitation
12.	Radical Lifetimes	Chemical Processes in Fluids	General

Table 2. Orbiter Power Availability to Payload

	AVERAGE	PEAK
POWER, KW		
LAUNCH	1.0	1.5
ON-ORBIT NORMAL OPERATIONS	7.0	12.0
ON-ORBIT DEGRADED OPERATIONS	5.0	8.0
REENTRY	1.0	1.5
VOLTAGE, VOLTS - DC		
CONTINUOUS DUTY	24 TO 32	
INTERMITTENT DUTY	23 TO 32	
RIPPLE	4 (PEAK TO PEAK)	
ENERGY, KWH	950	
SPACELAB PAYLOAD ALLOCATION, KW		
MODULE ONLY	4.0	9.0
MODULE AND PALLET	4.8	9.0
PALLET ONLY	4.8	9.0
PALLET ELEMENT	1.5	2.0
ENERGY ALLOCATION, KWH		
MODULE ONLY	595	
MODULE AND PALLET	595	
PALLET ONLY	730	

Additional power sources may be provided to supply electrical power requirements that exceed the allocation of electrical power from the Orbiter. The power sources considered are supplemental and/or peaking battery kits and the use of a Power-Heat Rejection Kit (PHRK) that contains up to two Shuttle-type fuel cells and the necessary plumbing, controls, reactants and tankage to satisfy the SPA experiment requirements (see Section 3.1.3). The PHRK would provide up to 14 KW of continuous power and peaks of up to 24 KW for 15 minutes. For purposes of this analysis an emergency peaking of 10 KW per fuel cell or 20 KW total for one hour was also assumed.

The use of the experiment payload allocation from the Orbiter and the PHRK will provide electrical power to the SPA experiments of from 4.0 to 18.8 KW continuously and peaks of up to 33 KW for 15 minutes. The Spacelab electrical power requirements to support its subsystems are not fixed, however, and any increase in these requirements will result in decreases in the power available to the experiments.

To assess the capability of the electrical power allocations to satisfy the SPA experiment requirements the sustaining and peak experiment electrical power requirements at the source for each of the 12 identified experiments are summarized in Figure 1 and 2, respectively, for comparison with the power allocations from the Spacelab and the PHRK. On these figures are also shown, for comparison, the average and peak electrical power capabilities of one and two fuel cells.

The sum of the experiment equipment, the core subelement equipment and the thermal control equipment requirements are reflected back to the power source assuming a 90% power factor, a 70% inverter efficiency, a 2% factor for line losses and a 10% contingency.

The average power is the average power over the total elapsed experiment time for each experiment and is from turn-on of the core equipment (zero minutes). The core equipment and thermal control equipment are on continuously during these durations and require slightly higher than 4 KW at the power source. The experiment equipment operates for a shorter period of time, depending on the experiment, and the sustaining power as shown in the figure is the average power of all equipment during the

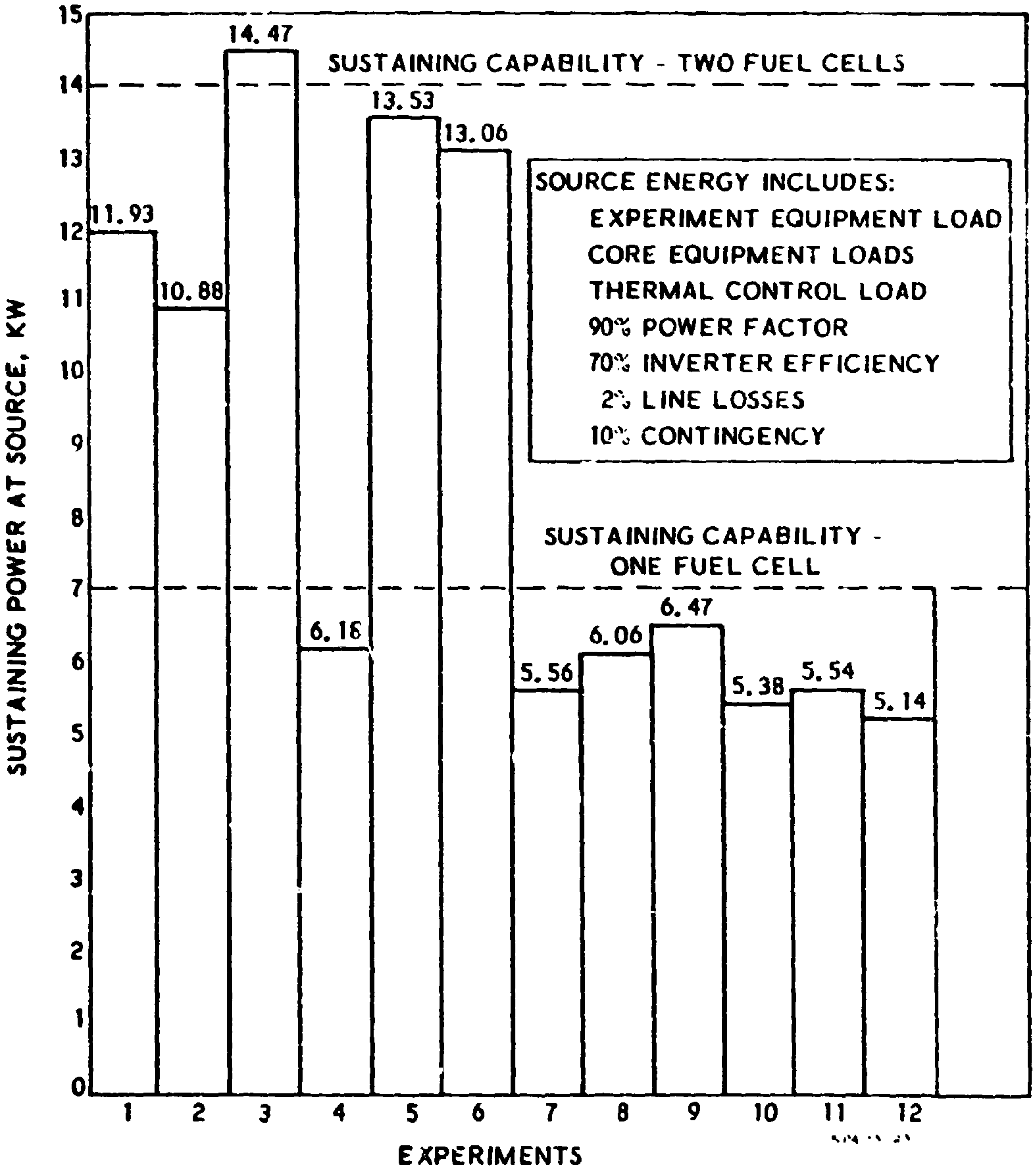


Figure 1. Sustaining Experiment Power (at Power Source)

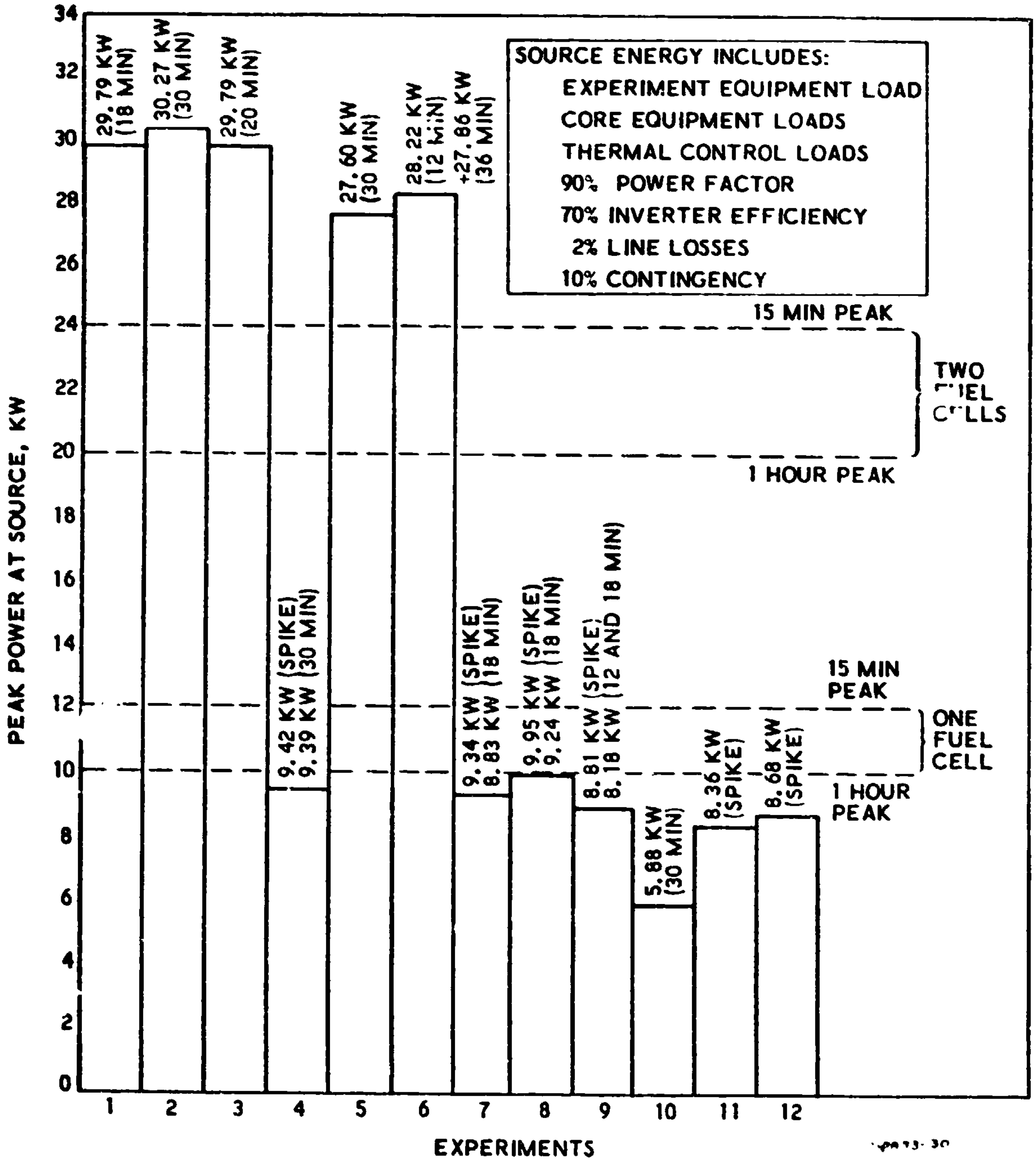


Figure 2. Peak Experiment Power (at Power Source)

shorter time duration.

The peak power requirements also show the duration of the peaks. Where more than one peak occurs of similar magnitude both are shown. Where two identical peaks occur with only several minutes of separation they are represented as one peak with a total duration equal to the sum of the duration of each peak.

The energy requirements for one cycle of each of the twelve experiments were also determined and are summarized in Figure 3. The energy requirements are at the energy source and include the total energy from turn-on to turn-off of the core and thermal equipment.

The sustaining and peak power requirements for each of the twelve experiments presented in Figures 1 and 2 are relatively high. One reason is because commercial equipment designers have not had a great deal of concern about power consumption. Also, the electrical load analyses conducted during this study are based upon typical equipment and some worst-case conditions. When a decision was required under the above conditions a worst-case or near-worst-case condition was usually selected. A refinement or scrubbing of the experiment equipment requirements and time lines and possible increases in power conditioning efficiencies by identifying equipment that does not require regulated sine wave AC could result in some decrease in the power requirements.

The sustaining and peak SPA experiment electrical power requirements at the source were compared to the average and peak electrical power allocations to the SPA experiment from the Shuttle Orbiter/Spacelab and from the PHRK as shown in Table 3. The "x's" on the table indicate that the allocation concept average or peak power capabilities satisfy the sustaining or peak power requirements,respectively, of that experiment. The Spacelab allocation from Concept 1 of 4 to 4.8 KW average does not satisfy any of the 12 SPA experiment sustaining power requirements. However, five of the experiments peak power requirements are satisfied by the 9 KW peak Spacelab allocation. The use of a PHRK with one fuel cell (Concept 2), 7 KW average and 12 KW for 15 minutes, satisfies both the sustaining and peak requirements of seven of the twelve SPA experiments. Concepts 1 and 2 were combined to obtain Concept 3 to give an average capability of 11 to

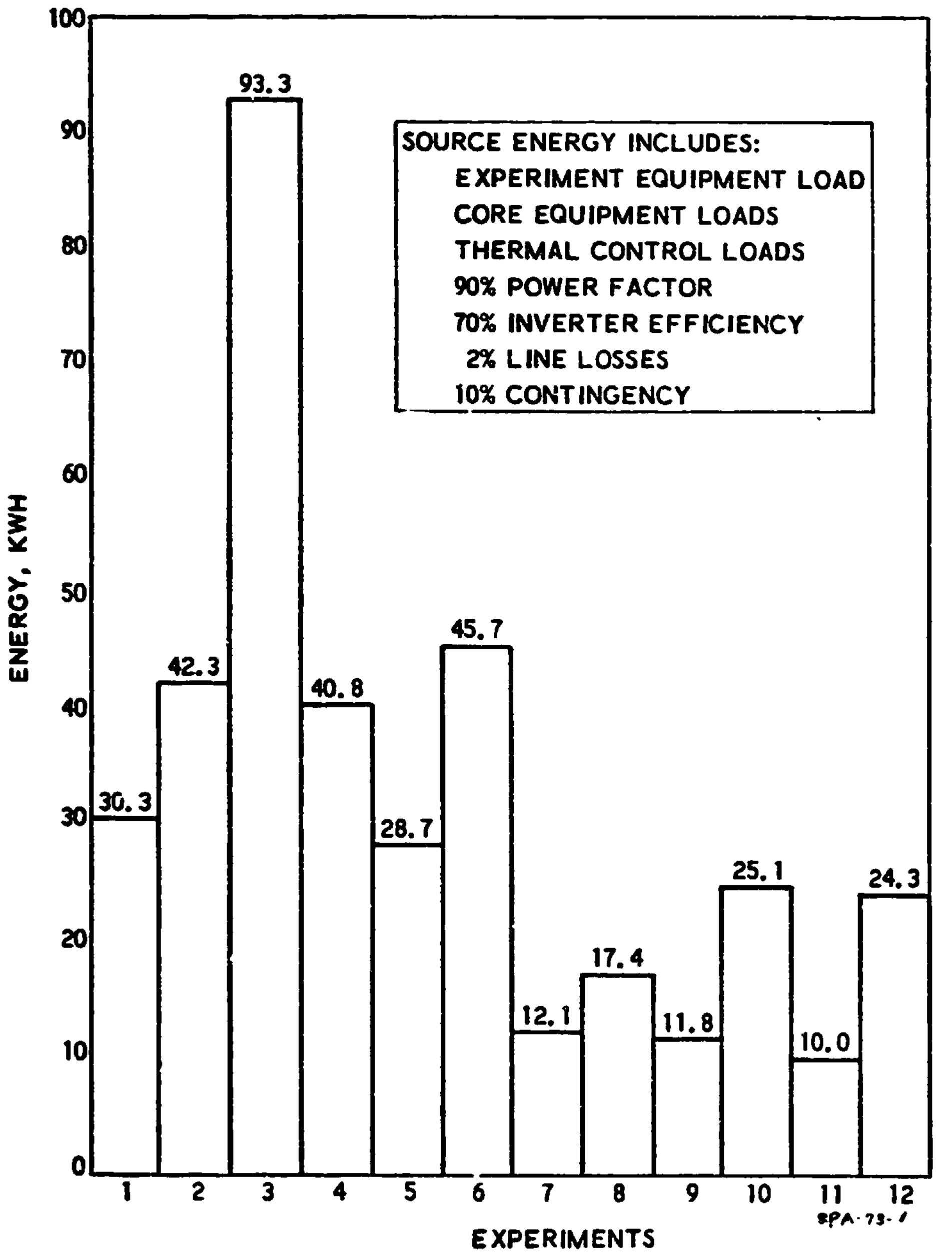


Figure 3. Experiment Energy Requirement at Power Source (Energy per Experiment Cycle)

Table 3. SPA Experiment Power Source Accomodation

EXPERIMENT NO.	EXPERIMENT NAME	POWER SOURCE CONCEPTS									
		1 SPACE LAB ALLOCATION ONLY[1]		2 POWER-HEAT REJECTION KIT[2] ONE FUEL CELL		3 SPACE LAB ALLOCATION PLUS POWER-HEAT REJECTION KIT ONE FUEL CELL		4 POWER-HEAT REJECTION KIT TWO FUEL CELLS		5 SPACE LAB ALLOCATION PLUS POWER HEAT REJECTION KIT TWO FUEL CELLS	
		AVERAGE 4 TO 4.8 KW	PEAK 9 KW	AVERAGE 7 KW	PEAK 12 KW[3]	AVERAGE 11 TO 11.8 KW	PEAK 21 KW	AVERAGE 14 KW	PEAK 24 KW	AVERAGE 18 TO 18.8 KW	PEAK 33 KW
1	METALLURGICAL - FURNACE							X		X	X
2	METALLURGICAL - LEVITATION					X		X		X	X
3	CRYSTAL GROWTH - FURNACE									X	X
4	CRYSTAL GROWTH - LEVITATION			X	X	X	X	X	X	X	X
5	GLASS TECHNOLOGY - FURNACE							X		X	X
6	GLASS TECHNOLOGY - LEVITATION							X		X	X
7	BIOLOGY APPLICATIONS - STATIONARY COLUMN		X	X	X	X	X	X	X	X	X
8	BIOLOGY APPLICATIONS - CONTINUOUS FLOW			X	X	X	X	X	X	X	X
9	PHYSICAL PROCESSES IN FLUIDS - LEVITATION		X	X	X	X	X	X	X	X	X
10	PHYSICAL PROCESSES IN FLUIDS - GENERAL		X	X	X	X	X	X	X	X	X
11	CHEMICAL PROCESSES - LEVITATION		X	X	X	X	X	X	X	X	X
12	CHEMICAL PROCESSES - GENERAL		X	X	X	X	X	X	X	X	X

SPA 73-31

NOTE:
1. SPACELAB SUBSYSTEM SPECIFICATION, ISSUE 3, REVISION 2, ESRO, 1973 OCTOBER 15.
2. FUEL CELL POWERPLANT, PROCUREMENT SPECIFICATION, MC464-0115, SPACE DIVISION, NAR, 1973 MAY 10.
3. PEAK POWER CAPABILITY IS 12 KW for 15 MIN AND 10 KW FOR ONE HOUR PER FUEL CELL.

*Indicates that the allocation concepts average or peak power capabilities satisfy the sustaining peak power requirements, respectively, of the experiment.

11.8 KW and 21 KW peak. This concept offers no significant advantage over Concept 2 as the sustaining power requirement of only one additional experiment is satisfied; no additional peak requirements are satisfied by this concept. A two-fuel-cell PHRK, with a capability of 14 KW average and 24 KW peak for 15 minutes, (Concept 4) satisfies eleven of the twelve SPA experiment sustaining power but only seven of the SPA experiment peak power requirements. All of the experiments' sustaining and peak power requirements are satisfied by the average capability of 18 to 18.8 KW and peak capability of 32 KW for 15 minutes for Concept 5.

To perform all of the twelve identified SPA experiments requires a two-fuel-cell PHRK in addition to the Spacelab experiment allocation. A significant increase in the Spacelab subsystem requirements will result in a significant decrease in the power allocated to the experiments from the Spacelab and could result in Concept 5 not being able to satisfy all of the experiment requirements. If the experiment allocations as indicated in Table 3 are derated then, as can be seen, the number of experiments that can be operated is decreased. Without the PHRK none of the experiments are fully satisfied

3.1.2 Definition of Power Source - Fuel Cells

To properly determine the electrical power requirements it is necessary to design and/or to know the characteristics of the electrical power source and to be able to reflect the loads to the source. This section will define and describe the electrical power source, as much as is available.

The electrical power source that supplies electrical energy to the SPA experiments will be Shuttle type fuel cells. The fuel cells may be the Shuttle fuel cells, the PHRK (see Section 3.1.3) fuel cells or both. Two different fuel cells are being considered for the Shuttle Orbiter and whichever one is selected by NASA-JSC will be used for all applications to avoid duplication of development. Because a fuel cell has not presently been selected the manufacturers are still in a competitive mode and detailed data are not readily available. Although the two types of fuel cells under development are required to meet a common specification, they differ in many respects particularly in the type of electrolyte used. The latest available data will be presented. In most cases the worst case

conditions of the known fuel cell characteristics were used in analyses.

The two fuel cell types that are being considered for the Shuttle Orbiter are a matrix fuel cell proposed by Pratt and Whitney and an ion exchange fuel cell under development by General Electric. Each of the fuel cell electrical power generating systems contain the fuel cell stack, valves and plumbing for reactant control, a coolant pump, water separator, and heat exchanger. The design and performance characteristics of both fuel cell types are summarized in Table 4.

More detailed and up to date characteristics of the fuel cells are contained in the summary in Table 6. It is apparent that some of these characteristics are still changing but not significantly. Selection of a fuel cell manufacturer should result in more firm characteristics. The characteristics shown were used in the design of the PHRK and for the thermal control interface designs. Each of these sections contain additional data on the fuel cell generating system that applies to their design.

Several thermal interfaces between the electrical power and thermal control subsystems were evaluated during the study. The primary interface is the dissipation of all electrical energy consumed by the experiments. That is, the energy under the experiment power source profiles must be dissipated by the thermal control subsystem. The dissipation of this energy requires additional electrical energy for operation of the thermal control equipment which in turn increases the electrical energy that must be dissipated. Other thermal interfaces that were considered are the dissipation of heat from the fuel cells and the by-product water produced by the fuel cells for possible use by the thermal control subsystem.

Based upon the experiment load requirements and assuming the use of the PHRK (Section 3.1.3), a thermal control pump system electrical power requirement of 470 watts continuous was determined to satisfy the thermal control subsystem requirements. The approach assumes that any experiment equipment that receives power from the Spacelab uses the Spacelab thermal control capability.

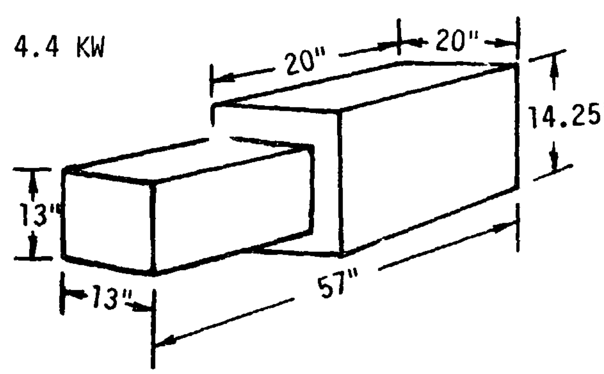
Table 4. Fuel Cell Performance

	Matrix	Ion Exchange
Vendor	P & W	GE
Electrolyte	KOH	Solid polymer
V_{oc} (per cell)	1.10 V	1.23 V
V_0 at rated load (per cell)	0.97 V	0.93 V
Cooling Method	Pumped liquid coolant plus open cycle H_2O boiling at backup	Pumped liquid coolant
Rated Output Power	7 kW	7 kW
Maximum Output Power	14 kW (with open cycle cooling)	14 kW (short duration)
Nominal current density	1300 amp/m^2 (120 amp/ft^2)	1400 amp/m^2 (130 amp/ft^2)
Stack Temperature	88°C (190°F)	82°C (180°F)
Reactant Inlet Pressure	420 kN/m^2 max (60 psia)	350 kN/m^2 max (50 psia)
Heat generated at rated load	4.4 kW	4.35 kW
Efficiency	61%	62%
Inherent Voltage Regulation (0.5 to 7.0 kW)	± 5%	± 5%
Short circuit current	3000 amp	800 amp
Weight	110 kg (245 lb)	146 kg (325 lb)
Specific Weight	16 kg/kW (35 lb/kW)	21 kg/kW (46 lb/kW)
Specific Reactant Consumption	0.4 kg/kWH (0.9 lb/kWH)	0.4 kg/kWH (0.9 lb/kWH)

SPA 74-115

NOTE: As of July 1974, it is understood that the P & W Fuel Cell has been selected.

Table 5. Shuttle Fuel Cell Characteristics

LIFE WITHOUT MAINTENANCE	2,000 HR MINIMUM 50 CYCLES (START-STOP) 9000 KWH
LIFE WITH MAINTENANCE	5,000 HR 125 CYCLES (START-STOP) 22,500 KWH
SHELF LIFE	10 YEARS
VOLTAGE	40 VOLTS (V_{oc}) 27.5 - 32.5 V_{dc} @ 2.0 TO 12.0 KW
POWER	2.0 TO 7.0 KW STEADY STATE UP TO 12 KW FOR 15 MINUTES UP TO 10 KW FOR 1 HR (EMERGENCY)
OVERLOAD	545 AMPS FOR 1 MINUTE MINIMUM
REACTANTS	GASEOUS HYDROGEN GASEOUS OXYGEN
PURGING	H_2 AND O_2 12 HOUR MINIMUM INTERVAL
REACTANT CONSUMPTION	0.9 LB PER KWH
HEAT GENERATED (RATED LOAD)	4.4 KW
SIZE ALL DIMENSIONS ARE MAXIMUM	
WEIGHT	245 LB (P & W) 325 LB (GE)
EFFICIENCY	61 - 62%
TEMPERATURE (OPERATING)	195° TO 230°F (90.6 TO 110.0°C) P & W 175° TO 200°F (79.5° TO 93.3°C) GE

SPA 74-115

The PHRK has a limited radiator area and additional cooling capability is required, therefore, the fuel cell by-product water is made available for this purpose. The water production rate for each fuel cell in pounds per hour is shown in Figure 4 as a function of net power output of the fuel cells in kilowatts. As noted the water production rate for both the General Electric and Pratt and Whitney fuel cells is near the maximum rate shown. The water will be delivered to a water storage tank that contains a positive expulsion system to allow the water to be used for thermal control.

As an aid in the definition of requirements and the design of the thermal control subsystem in the PHRK the heat rejection and coolant exit temperatures for both the General Electric and the Pratt and Whitney fuel cells are presented in Figure 5 as a function of gross power output from the fuel cells in KW. The individual fuel cells will operate between 2 KW and 12 KW each. With both fuel cells operating the minimum power will be 4 KW. The data presented in Figure 5 represents typical parameters rather than final design values.

The heat rejection requirements for either of the fuel cell types is not significantly different. The differences in the coolant exit temperatures are believed to be primarily due to coolant flow rates but this has not been verified. A fuel cell manufacturer has not presently been selected; however, for purposes of this study the worst case data are assumed relevant.

3.1.3 Power/Heat Rejection Kit

As previously discussed in Section 3.1.1 supplemental and/or peaking electrical power sources are required to satisfy the SPA experiment electrical power requirements. This power must be kitted. Two types of kits were considered; a battery kit for supplemental and/or peaking requirements and a Power-Heat Rejection Kit (PHRK) for supplemental power requirements. The latter was selected for detailed analysis and is discussed here.

A PHRK supporting the Spacelab offers a solution to satisfy the SPA experiment power and thermal control requirements. Kit packaging concepts

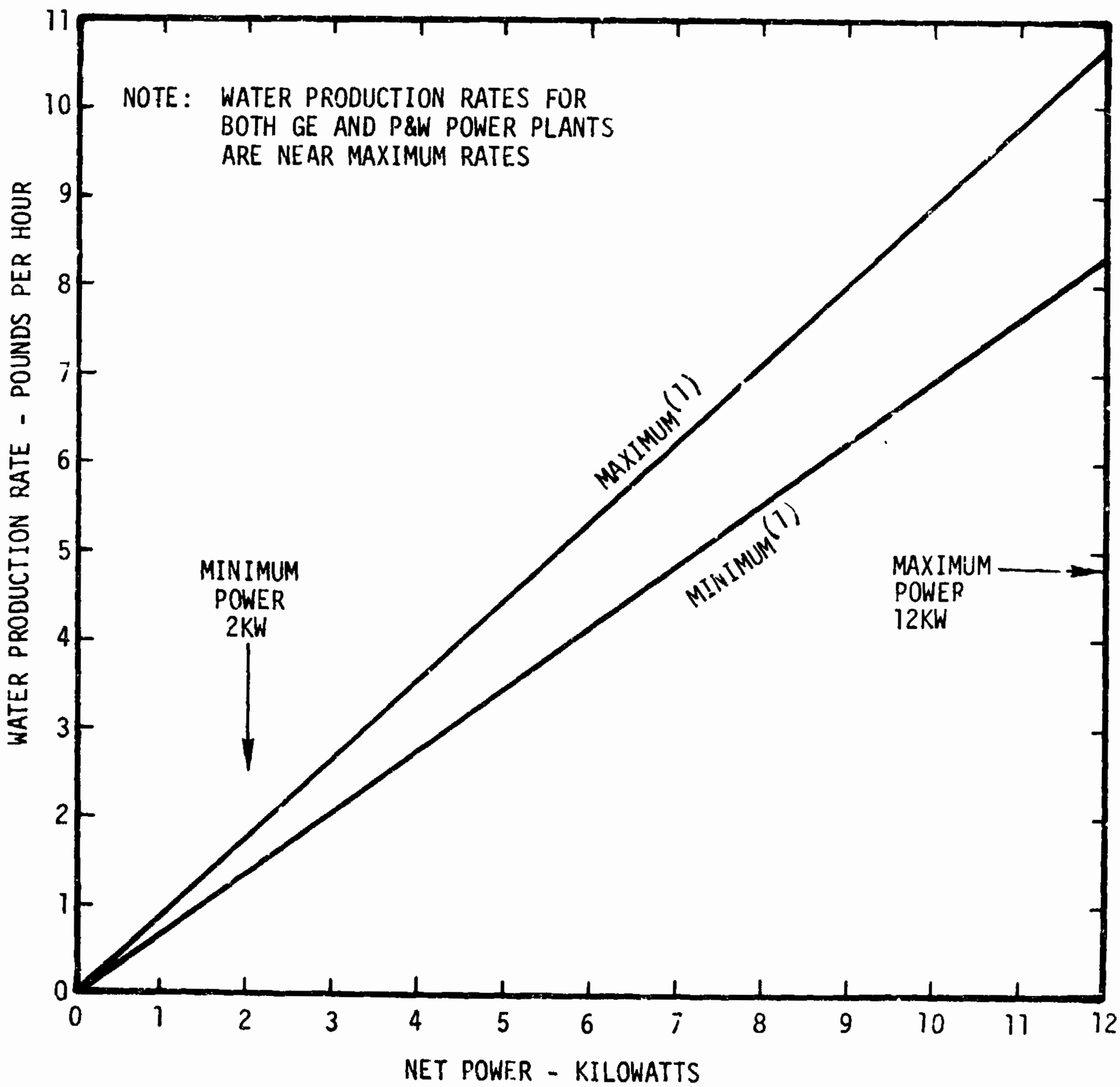


FIGURE 4 . Fuel Cell Power Plant Water Generation Rate

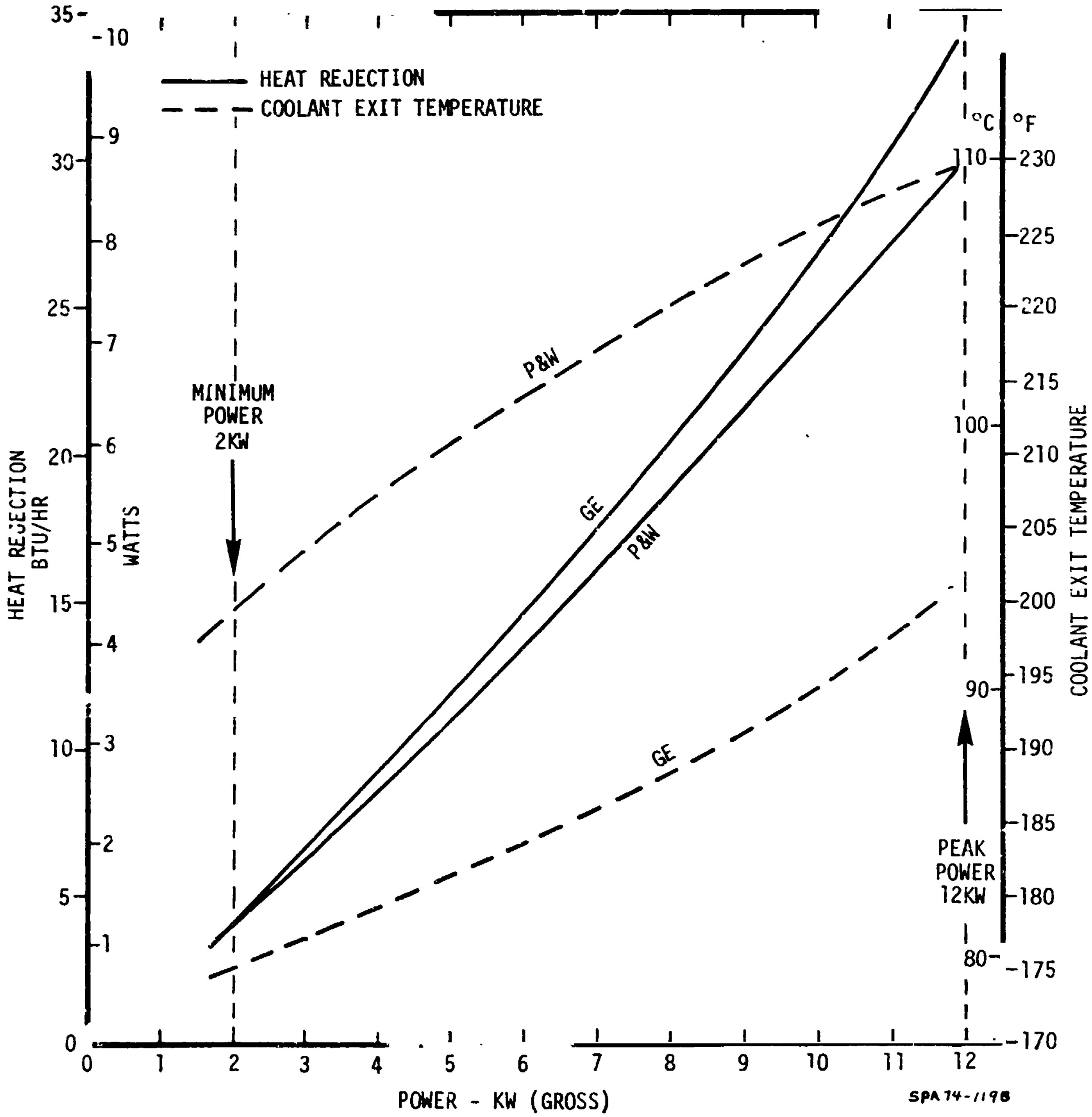


Figure 5. Fuel Cell Module Heat Rejection & Coolant Exit Temperature

and equipment storage are shown and discussed in Sections 4.0 and 5.0. The electrical power portion of the Kit and its interfaces will be discussed in this section.

The electrical power subsystem of the PHRK is made up of two fuel cells, oxygen and hydrogen reactant tank assemblies, water storage tanks, plumbing, cabling and inverters to convert the nominal 28VDC fuel cell output to AC power. A simplified block diagram of the electrical power subsystem is shown in Figure 6. The electrical power system has an output from both fuel cells of up to 14 KW average with peaks of up to 24 KW for up to 15 minutes duration. Higher peaks can be sustained for shorter periods of time and lower peaks for longer periods. The fuel cells have an emergency capability of 10 KW for one hour which was assumed to be a capability for this study. The reactant tank assemblies provide for cryogenic storage of hydrogen and oxygen to provide about 1000 KWH of energy.

A flow diagram of a fuel cell power plant is shown in Figure 7. This is a simplified diagram based upon the Shuttle Orbiter fuel cell design. The subsystem is made up of two fuel cells with each of their interfaces tied together as shown. The fuel cell power plant interfaces are the oxygen and hydrogen reactant inlets, vents for oxygen and hydrogen purge and water, coolant inlet from and outlet to a thermal control heat exchanger, and the principal outputs of electrical power to the loads and by-product water to storage tanks.

Oxygen and hydrogen are supplied to the fuel cell inlet; the reactants are heated within the power plant before entering the cell stack where electrical power is generated by the electrochemical reaction of oxygen and hydrogen. The electrical power is delivered to the equipment loads through the power conditioning and distribution elements. This reaction has an efficiency of about 60% resulting in the generation of heat which is carried away by the coolant loop. The coolant passes through the thermal control heat exchanger where the thermal control subsystem picks up the heat for dissipation. The water is collected in special storage tanks and is used to satisfy additional thermal control requirements, such as in flash cooling. It is not dumped for three reasons: (1) it can be

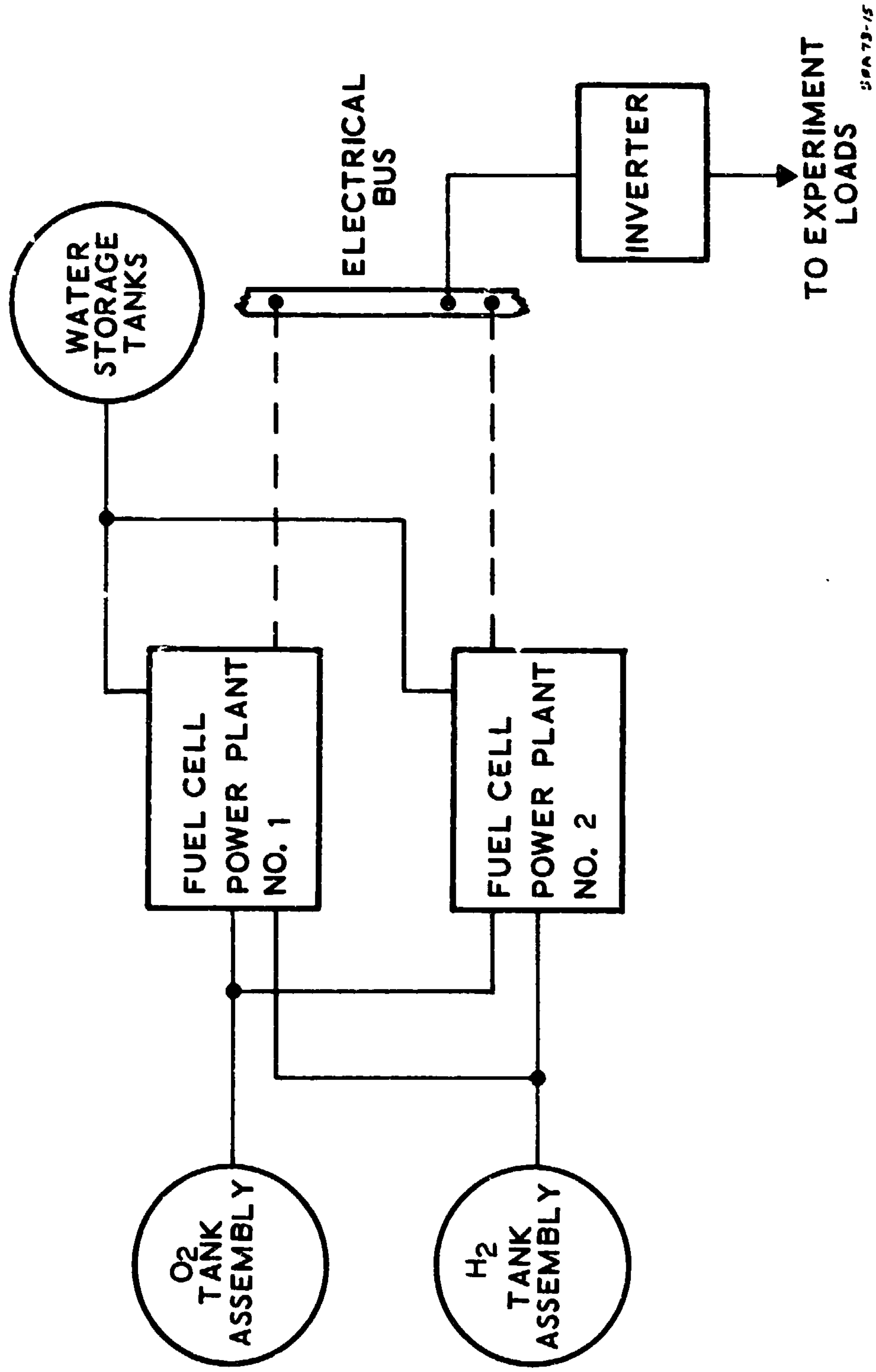


Figure 6. Fuel Cell Electrical Power Subsystem

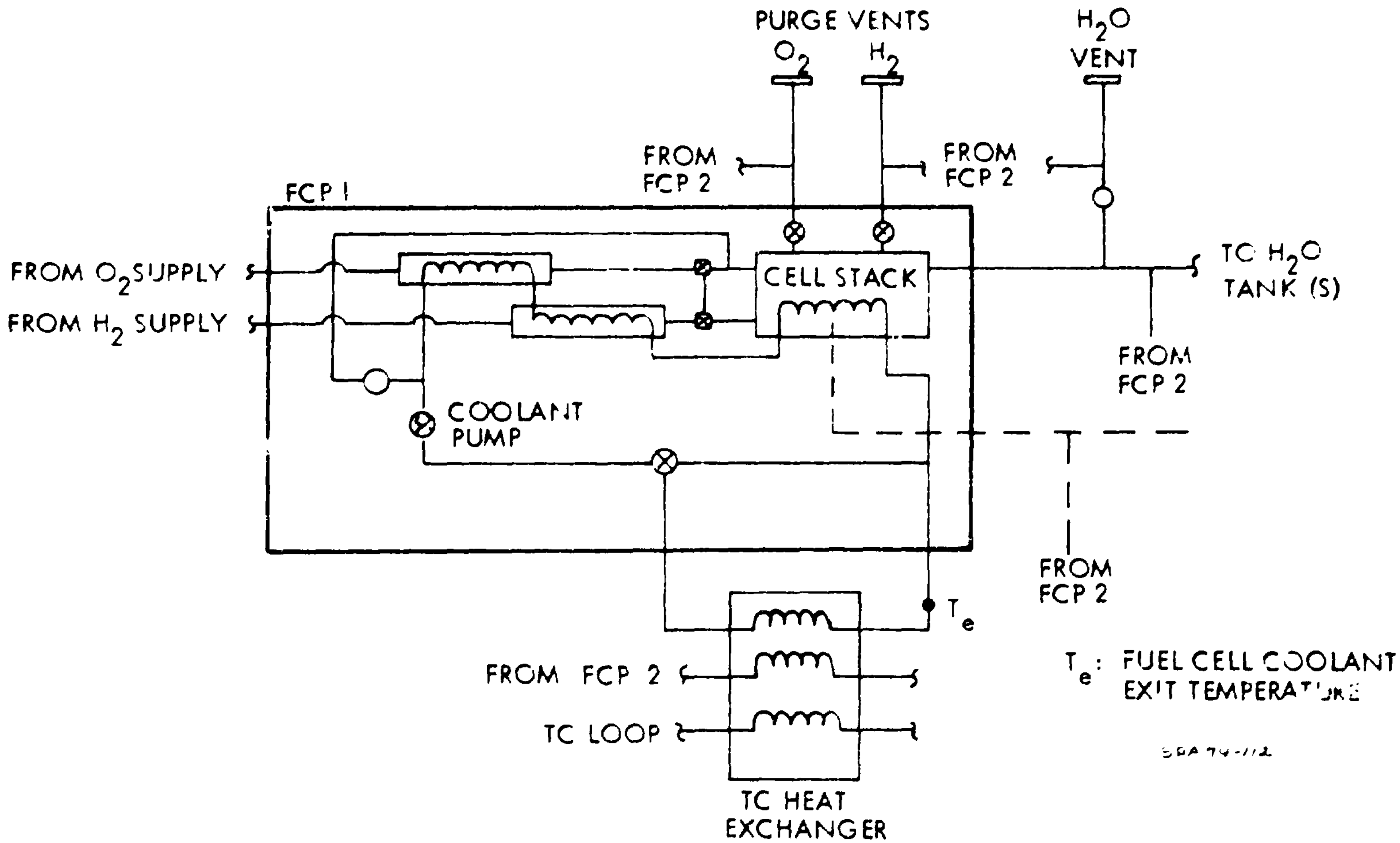


Figure 7. Fuel Cell Power Plant (FCP)

used to help maintain tne vehicie c.g. as the reactants are consumed; (2) it could affect the operation of some of the experiments; and (3) to accommodate the previously mentioned thermal control requirements The water tanks are sized to store all of the water that is produced by the fuel cells and not required by the thermal control subsystem. The fuel cell stack is purged by hydrogen and oxygen at minimum intervals of 12 hours.

Each power plant is capable of providing 27.5 to 32.5 volts of DC power over a power range of 2 to 1_ kW for 15 minutes. The design goal for operating life is 2,000 hours without maintenance and 5,000 hours with maintenance. This includes 50 start/stop cycles with no maintenance and 125 start/stop cycles with maintenance.

The source of energy for the fuel cells is provided by supercritical cryogenic storage dewars which supply oxygen and hydrogen to the fuel cell power plants The reactants stored in the dewars are maintained at a pressure greater than the fluid-critical pressure. Therefore, reactants are supplied in a single fluid state by simple pressure feed. The nominal pressure of 250 psia for hydrogen and 900 psia for oxygen is maintained by supplying heat to the fluid when the pressure in the dewars drop below a minimum allowed pressure limit. The reactant tank assembly for the PHRK is shown in Figure 8. The tank assemblies include the heaters, pumps, filters, valves, and control loops to maintain storage of the reactants and to supply them to the power plants. The interfaces for fill, drain, vent and supply are also shown. The PHRK is made up of one or more each of the oxygen and hydrogen tank assemblies.

3.1.4 Power Conditioning and Distribution

The electrical power distribution subsystem addresses SPA payload design problems dealing with power processing, distribution, and control as it emminates from the power source (fuel cells) to selected experimental equipment.

The electrical distribution subsystem provides the following functions to the electric power subsystem interface:

- Power switching and distribution to all experiments

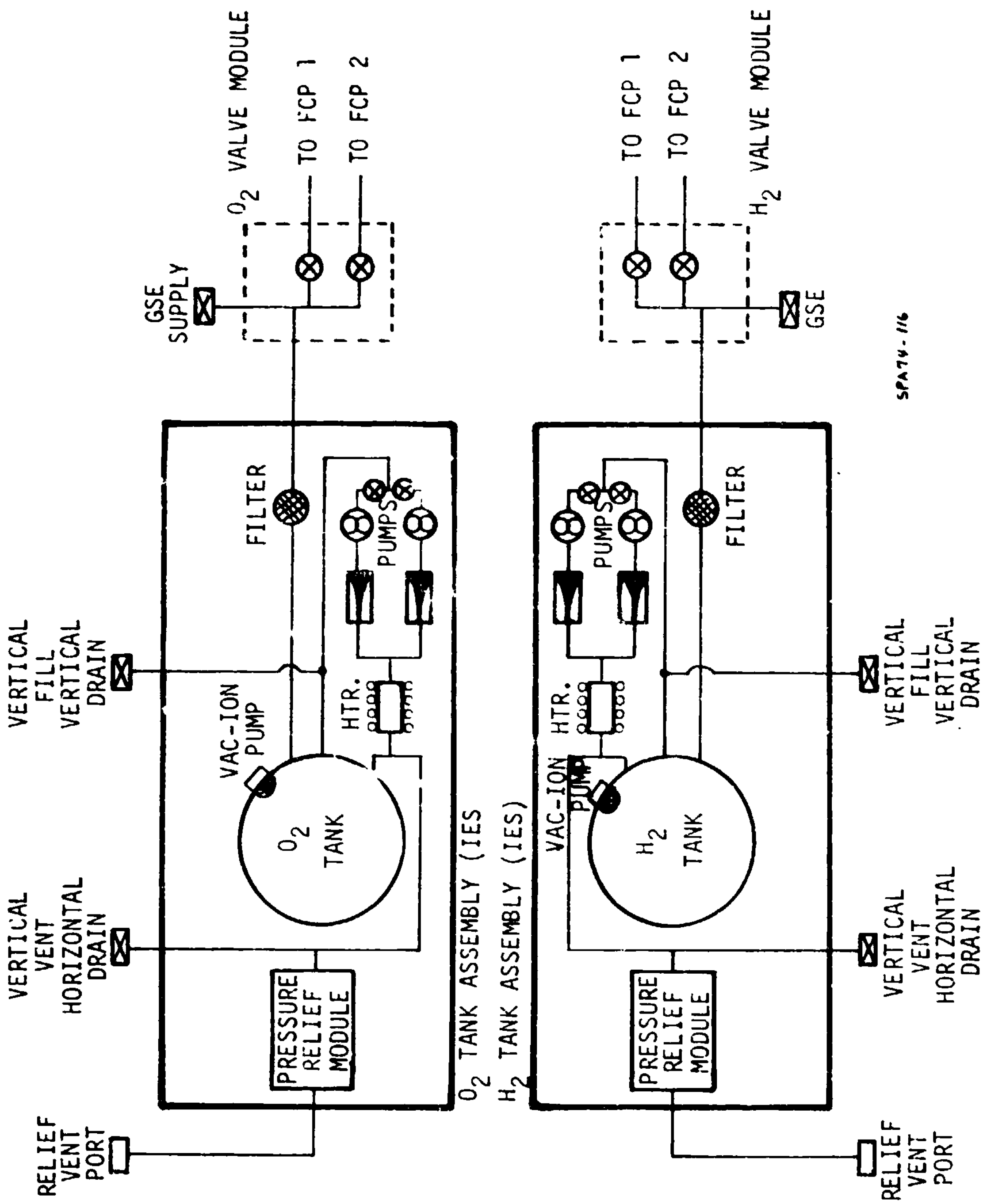


Figure 8. Power Reactant Storage Tank Assembly

- Signal distribution.
- Signal conditioning.
- Interconnection of all electrical interfaces.

The power distribution subsystem will be constrained in design by the following factors:

- The 28VDC fuel cell bus shall be protected by DC circuit breakers.
- The DC-AC inverters are to be self protecting for overvoltage on the input as well as overload and short circuit of the output.
- The low power output feeder lines (500VA) shall be protected by AC circuit breakers.
- The higher power output feeder lines shall be protected by fault detectors which will clear the faulted bus. Circuit breakers are not practical on the higher powered buses because insufficient overload current is available to trip the breakers, since the source is a current limited inverter.

3.1.4.1 Concepts and Alternatives

The electrical power distribution subsystem takes the available source power and distributes this power to the experimental equipment in a safe and efficient manner. The following distribution systems were considered:

- 28VDC distribution system
- 60Hz AC distribution system
- 400Hz AC distribution system
- 1600Hz AC distribution system

3.1.4.2 Evaluation and Comparison

The electrical power distribution subsystem selected for the Spacelab experiment equipment should interface with the commercially available experiment equipment with a minimum of modification.

The experiment equipment selected for the Spacelab mission are commercially available units operating from a 115V 60Hz or 400Hz bus. The majority of the units are rated for a 60Hz bus, but with minor

modifications, can be adapted to operate off of a 400Hz or higher frequency bus.

For high power experiment loads requiring precise power control, a higher frequency system is desirable. With a low frequency system, proportional control (phase control) is required to obtain the regulation accuracy whereas with a higher frequency system, zero switching control can be utilized. Proportional control of high power loads result in high EMI being generated since switching occurs during a cycle.

The 115VAC at 400Hz is selected for the low power experiment bus for the following reasons:

- Lower cabling weight than 28VDC,
- Minor or no modification required on experiment equipment.
- Voltage level can be changed readily by transformers.
- Availability of circuit breakers.
- Airborne qualified and specified by MIL-STD-704.

The 115VAC, 3 ϕ, 4 wire at 1600Hz or 1800Hz is selected for the high power experiment bus.

Table 6 provides a tradeoff in size and weight for DC to AC inverters for 60Hz, 400Hz and 1800Hz.

TABLE 6

DC to AC Inverter Size and Weight Comparison

Freq.	Output VA	Weight	Size
60Hz	1500VA	145 lb	17-1/4x15 9/16x10-1/2
		0.10 lb/VA	1.87 in^3/VA
400Hz	1500VA	115 lb	17-1/4x15 9/16x10-1/2
		0.07 lb/VA	1.87 in^3/VA
1800Hz	1800VA	50 lb	19 x 22 x 69
		0.028 lb/VA	1.60 in^3/VA

3.1.4.3 Concept Selection

The electrical distribution subsystem will be limited to the power sources and requirements that are available to the Spacelab from the Shuttle and any onboard primary or secondary sources of power as designated by the electrical power subsystem. The baseline power distribution system for the Spacelab is an AC system that utilizes 400Hz, single phase inverters for low power and 1800Hz or 1600Hz, three phase-4 wire inverters for high level power. An additional design constraint for power distribution is that manual switching be considered as baseline for the system. All power and signal distribution must consider the impact of electromagnetic interference and that sufficient safeguards be made available to minimize the effects of short circuits at one load from influencing other experiments.

Figure 9 presents a block diagram of the Spacelab power distribution system. Two isolated 28VDC primary power buses provide the power requirements for the experiment loads of the Spacelab.

Power conversion from 28VDC to 400Hz and 1800Hz AC is accomplished by static DC to AC inverters. For the 400Hz distribution bus, four 1500VA inverters are connected in parallel. The inverters are frequency and phase synchronized to prevent dynamic interactions and system instability. Each of the 1500VA inverters can be further divided into smaller VA rating inverters for redundancy consideration. The 1800Hz, 3 ϕ inverter shown as a single block can be made up of several inverters connected in parallel. When considering safety aspects of the system, the inverters are self protecting for overvoltage on the input as well as overload and short circuit of the output.

A variety of switches and sensors are needed for load and inverter ON/OFF control, for protection of the primary buses, and for removal of faulty loads and inverters. The input power junction box contains circuit breakers and fault sensors for inverter input power protection and switching. Circuit breakers can be used on low VA rated inverters since enough overload current is available from the bus to trip the breaker. As the VA rating of the inverter approaches the VA rating of the bus, circuit breakers will not be able to clear a fault and other means of fault

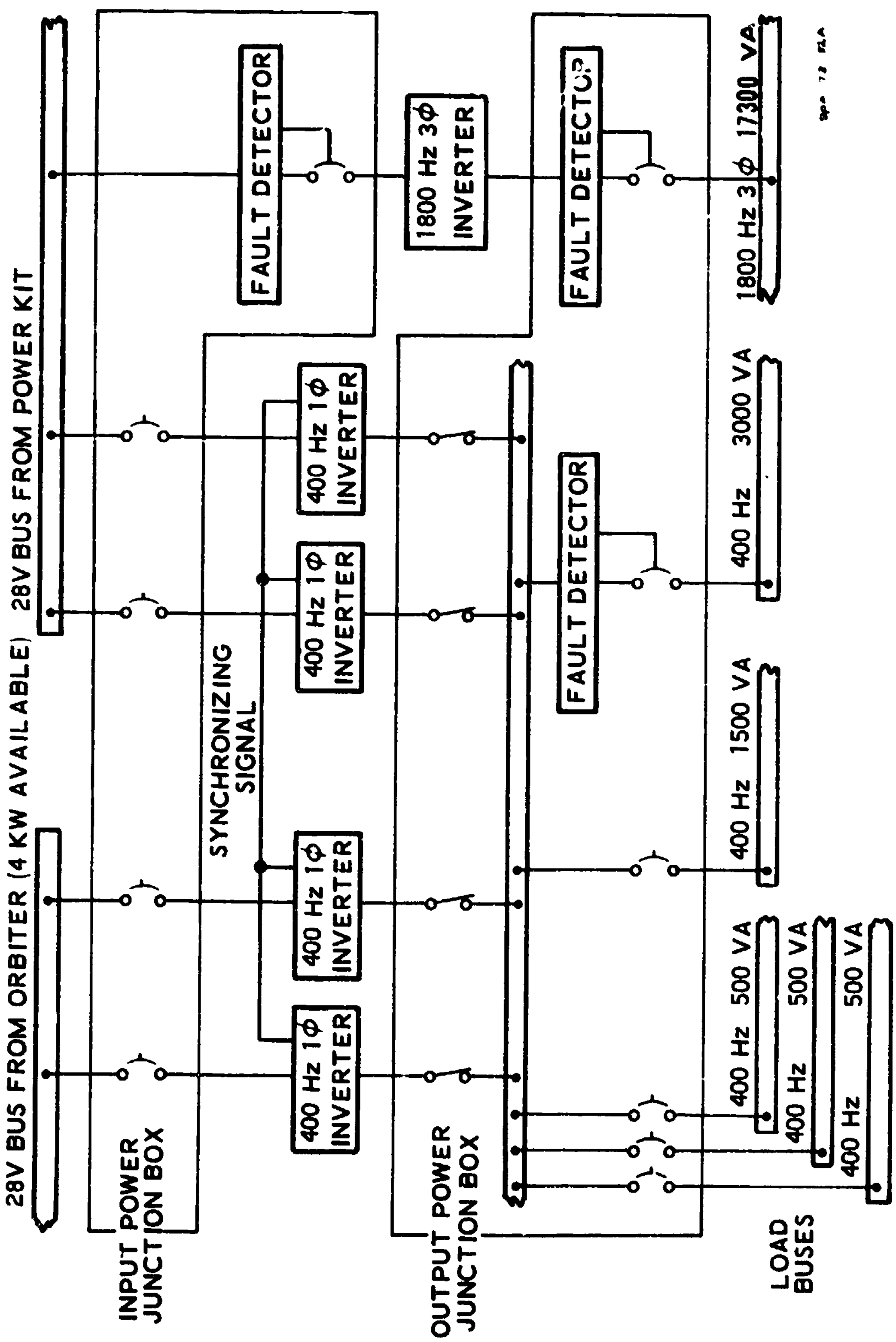


Figure 9. Spacelab Power Distribution

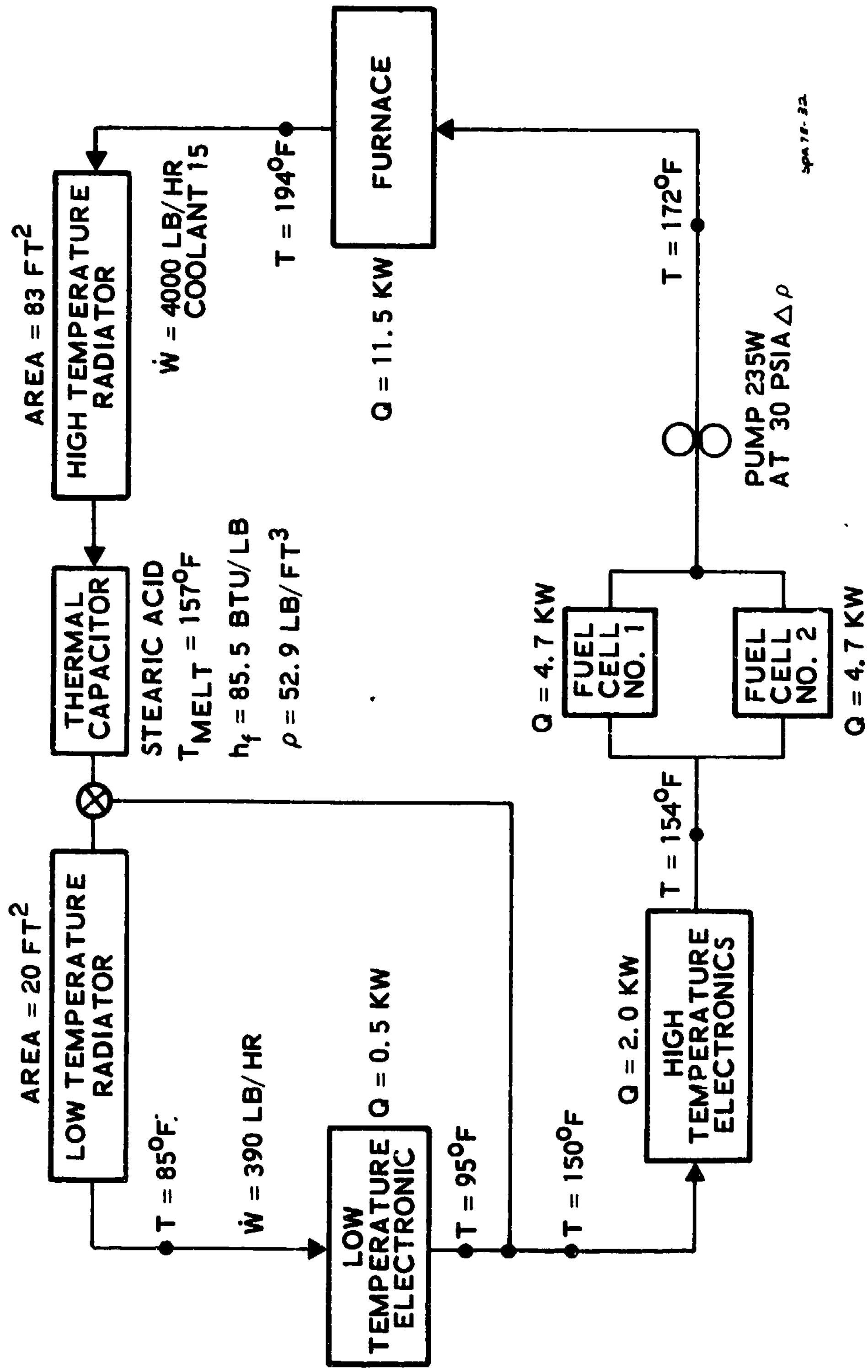


Figure 10 . Power/Heat Rejection Kit Heat Dissipation System

isolation must be used. A fault detector which senses both voltage and current is therefore used on all high power applications.

The output power junction box contains circuit breakers, switches and fault sensors for the load buses. The VA rating of the load buses should be kept as low as possible for protection purposes. A switch activated by fault detection circuitry is provided on the output of each inverter module so that a faulty module can be isolated from the bus.

Consideration should also be given to modularize both the input and output junction boxes into several separate modules so that in case of a major fault, some bus protection is provided by the physical separation of the switching elements. If all the circuit breakers and fault detectors were contained in a single enclosure, an overheating or fire could jeopardize the complete system.

3.2 THERMAL CONTROL SUBSYSTEM OF POWER/HEAT REJECTION KIT

The thermal control subsystem is designated the task of maintaining the environment of the experimental modules and payload equipment with specified temperature limits during the entire mission. Heat dissipation is accomplished by systems that combines cold plates, fans, heat exchanger, pumps, accumulators and related tubing and controls.

3.2.1 System Description

The Power/Heat Rejection Kit (PHRK) thermal control subsystem (TCS) consists of a pumped liquid loop which rejects thermal energy to space via a thermal radiator located on the exterior of the PHRK structure. A simplified schematic of the TCS is shown in Figure 10. As shown, the system is a liquid loop using two radiators to reject the thermal energy absorbed from the fuel cells, electronic equipment and furnace. The primary radiator is a nigh temperature radiator for high heat rejection and the secondary radiator is to provide temperature drop in approximately ten percent of the flow for cooling room temperature operating electronic equipment.

Since the area available for radiators is not sufficient to provide the waste heat rejection rate required by the high heat dissipating SPA payloads (e.g., Furnace Subelement Experiments), a thermal capacitor is

included in the system downstream of the primary radiator. The capacitor serves the function of storing the thermal energy that exceeds radiator capacity until such a time as the thermal load falls within radiator capability. At this time the thermal energy is removed from the capacitor and rejected to space through the radiators.

Figure 10 shows the PHRK TCS for the autonomous kit operation. For those missions where the kit is in support of SPA payloads within the Spacelab, the furnace and electronics portions of the coolant loop could be replaced with interface heat exchangers to provide cooling (Figure 11). These heat exchangers would be liquid-to-liquid type where the Spacelab coolant would be water (or another suitable coolant). It is desirable to keep Coolanol 15 from the inhabitable area of the Spacelab where furnace temperatures could exceed 160°F due to the fire hazard associated with the relatively low auto-ignition point of the Coolanol.

3.2.2 System Analysis

A system thermal analysis was conducted to assess the capabilities of the system described in Section 3.2.1. The pertinent parameters of the analysis are shown on Figure 10. As shown, a system flow rate of 4000 lb/hr was selected to maintain a relatively uniform temperature in the primary radiator to maximize radiator effectiveness. This high mass flow rate results in a high pump power requirement as shown on the figure.

The thermal capacitor characteristics chosen for the analysis are those of stearic acid which is a likely phase-change material for this type of system. It may prove desirable to select various phase-change materials depending on the particular mission to be flown (i.e., autonomous or Spacelab support role for the PHRK).

Based on the heat dissipations shown in Figure 10, the thermal control system heat rejection is shown in Figure 12. For the purpose of the analysis, the electrical power was assumed to be an instantaneous thermal load. In reality, the thermal mass associated with the electrical power dissipators will tend to reduce the peak load and/or shorten its expressed duration. The system heat rejection (expressed as allowable duty cycle for the electrical load) is shown for the baseline system and the addition of a water evaporator which utilizes the fuel cell water.

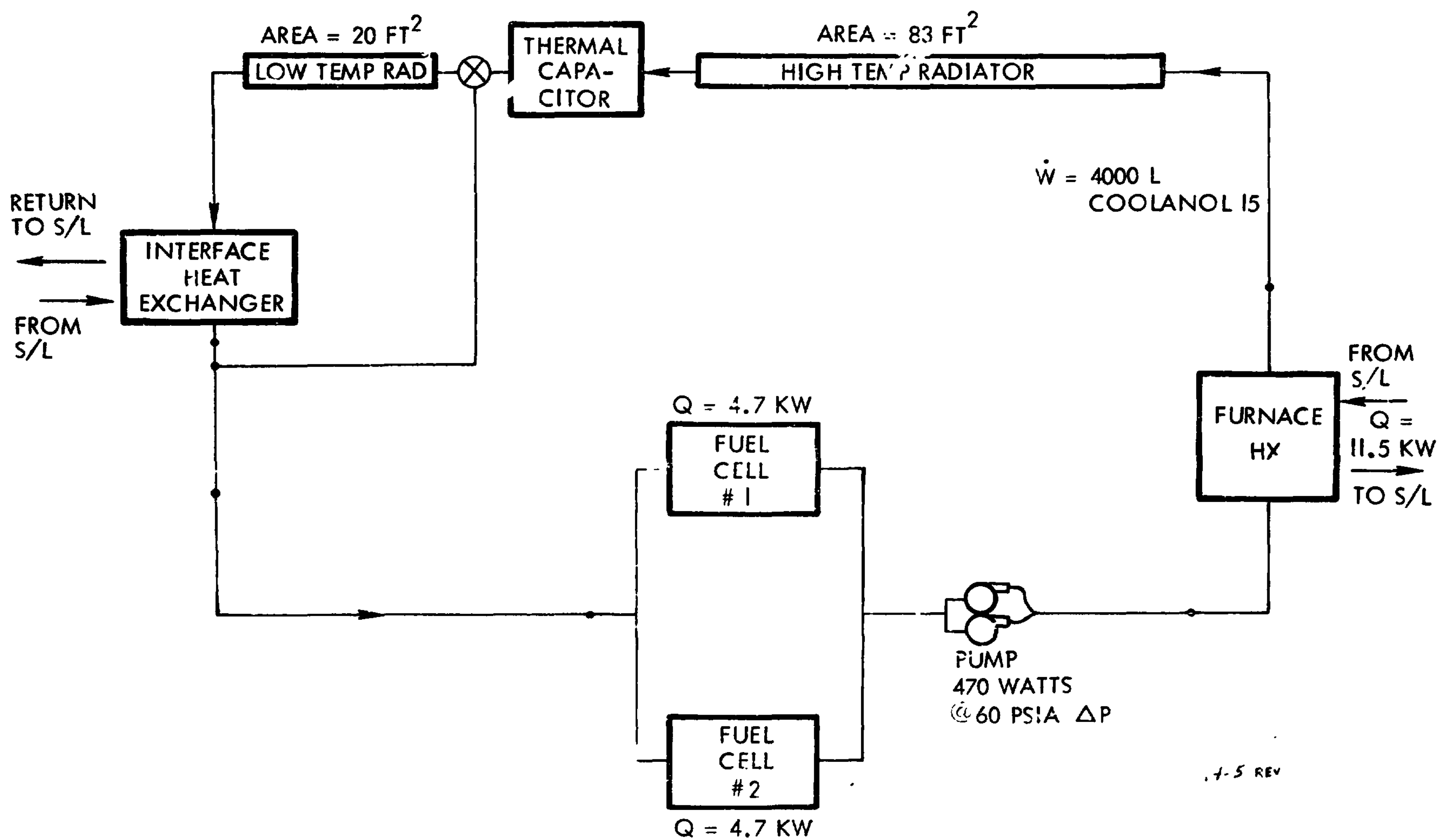


Figure 11. Power/Heat Rejection Kit's Heat Dissipation System (Internal Spacelab SPA Payloads)

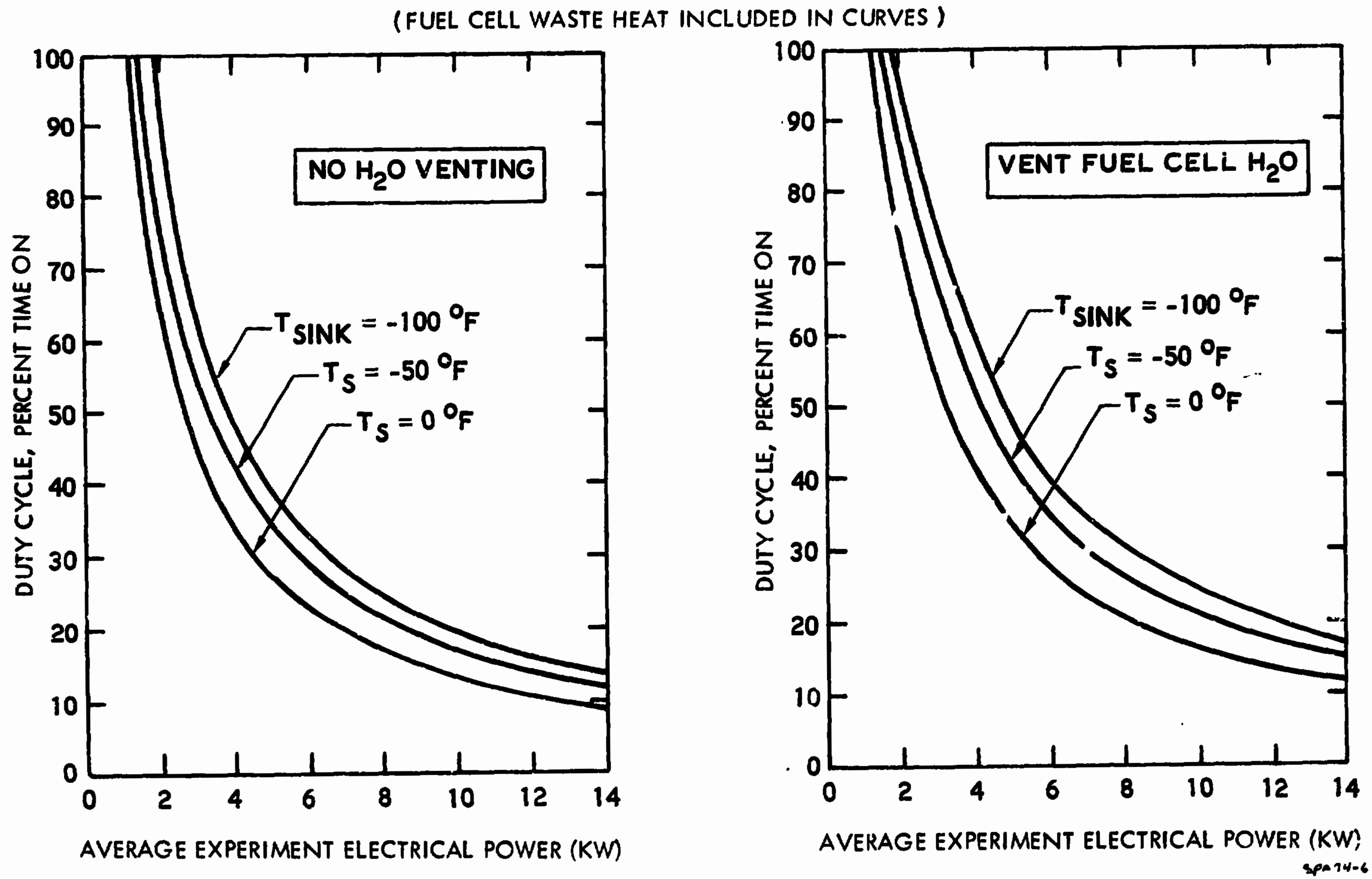


Figure 12. Allowable Duty Cycle for Kit

Also shown is the effect of radiator sink temperature which can materially increase the allowable peak power duty cycles.

Since the TCS capability is based on use of a thermal capacitor, the volume (or mass) of phase-change material can be varied to increase operating times for peak loads. The required weight (not including container) is shown in Figure 13. For example, to obtain a capability of a 4 KW peak for 30 minutes requires 100 pounds of heat sink material. Additional operating time can be obtained for a 4 KW load at the rate of 3.3 pounds of phase-change material per additional minute of operation.

If it is assumed that the inherent thermal mass of the PHRK is such as to increase the allowable duty cycle by a factor of 2 for short duration peak/loads (<2 hrs.) conducting a furnace subelement experiment (typical power profile shown in Figure 14 would require a thermal capacitor of approximately 500 pounds. If stearic acid is used as the phase-change material, approximately 9 cubic feet of material is required. This mass can be reduced to 400 pounds if the fuel cell water is utilized in an evaporator system integral with the TCS loop.

Table 7 gives a weight estimate of thermal capacitor required in the PHRK to meet the various experiment heat dissipation requirements for limiting case assumptions. Table 7, as such, illustrates the heat rejection capacity as the preeminent limiting interface subsystem. Stearic acid with a heat of fusion of 85.5 Btu/lb was assumed as the capacitor material. Capacitor weights were calculated for autonomous operation of the PHRK and for the case where 4.8 KW electrical equivalent heat is dissipated by the Spacelab. Also, the effect of venting fuel cell water with an evaporator is shown. The cases where zero capacitor weight is shown indicates that the PHRK can handle the required thermal load in a steady state mode. For all other cases the experiment repeat frequency must be constrained to allow the thermal capacitor material to re-solidify The repeat frequency can be determined from the duty cycle curves shown in Figure 13.

The requirement for thermal capacitor mass can be reduced by allowing heat leak from the PHRK structure to the Shuttle bay structure. With the Shuttle bay doors open the bay structure approaches -100°F. For a PHRK

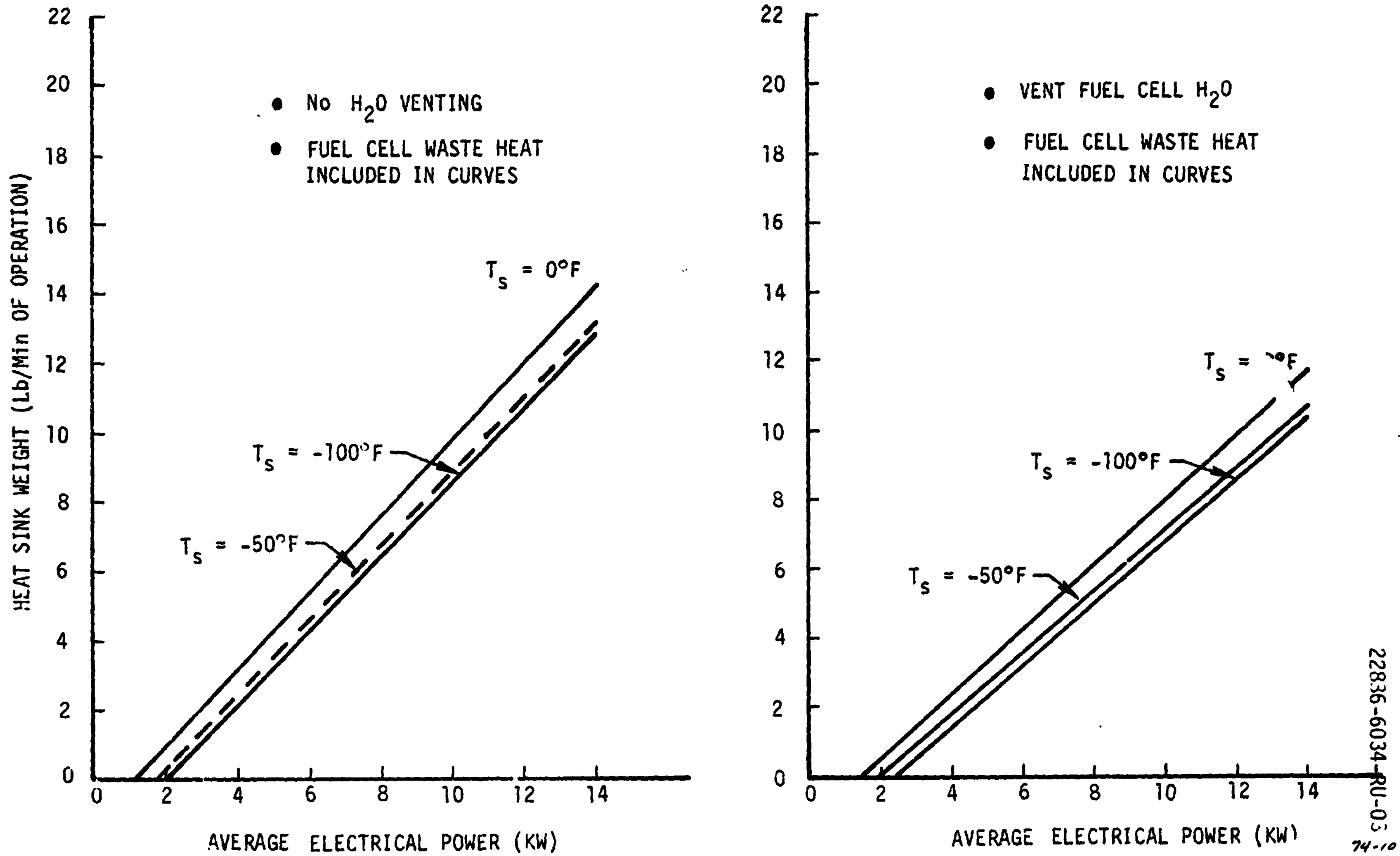
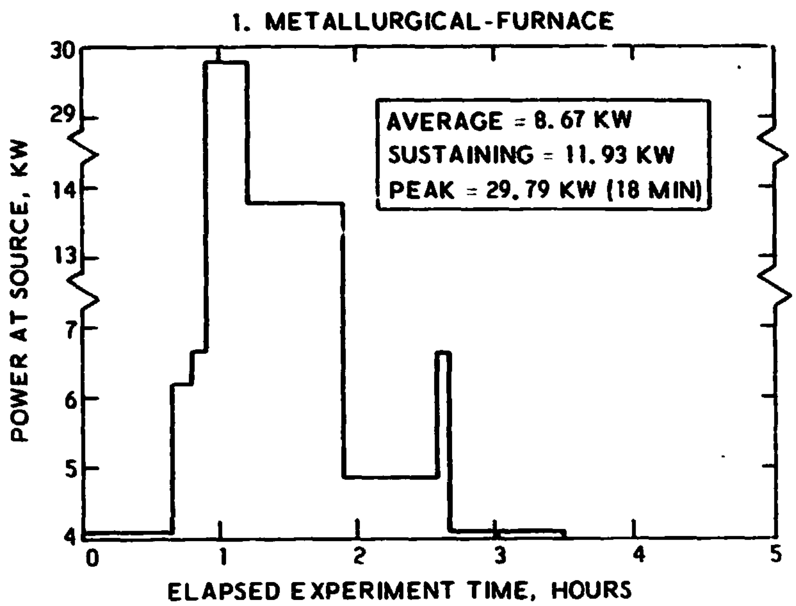
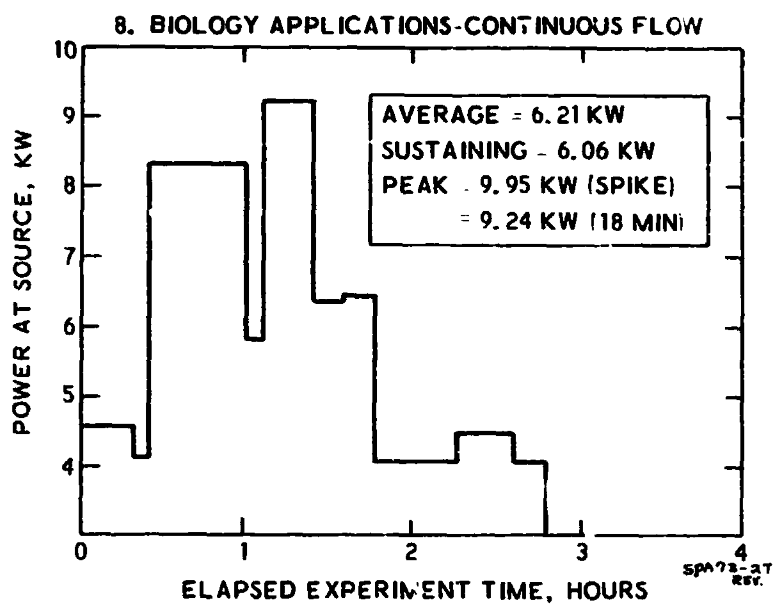


Figure 13. Required Heat Sink Material Weight





OTE: As of July 1974 the peak power of the unit B1E was revised to be 1.5 kW which will change the appearance of this power profile somewhat.

Figure 14. SPA Experiment Power Source Load Profiles

Table 7. Thermal Capacitor Weight Requirements

PAYLOAD NO.	THERMAL CAPACITOR WEIGHT							
	NO REJECTION BY SPACELAB				4.8 KW REJECTED BY SPACELAB			
	NO H_2O VENT		VENT FC H_2O		NO H_2O VENT		VENT FC H_2O	
	kg	lb	kg	lb	kg	lb	kg	lb
1	675	1490	571	1260	219	482	162	356
2	1010	2220	812	1790	380	836	282	620
3	2330	5130	1880	4130	1290	2840	1020	2250
4	795	1750	653	1440	0	0	0	0
5	695	1530	558	1230	316	695	240	530
6	1100	2430	880	1940	465	1025	354	780
7	252	555	200	440	0	0	0	0
8	366	805	288	635	0	0	0	0
9	239	527	184	405	0	0	0	0
10	476	1050	368	810	0	0	0	0
11	191	420	148	325	0	0	0	0
12	467	1030	361	795	0	0	0	0

NOTE: Based on -73C (-100F) sink temperature.

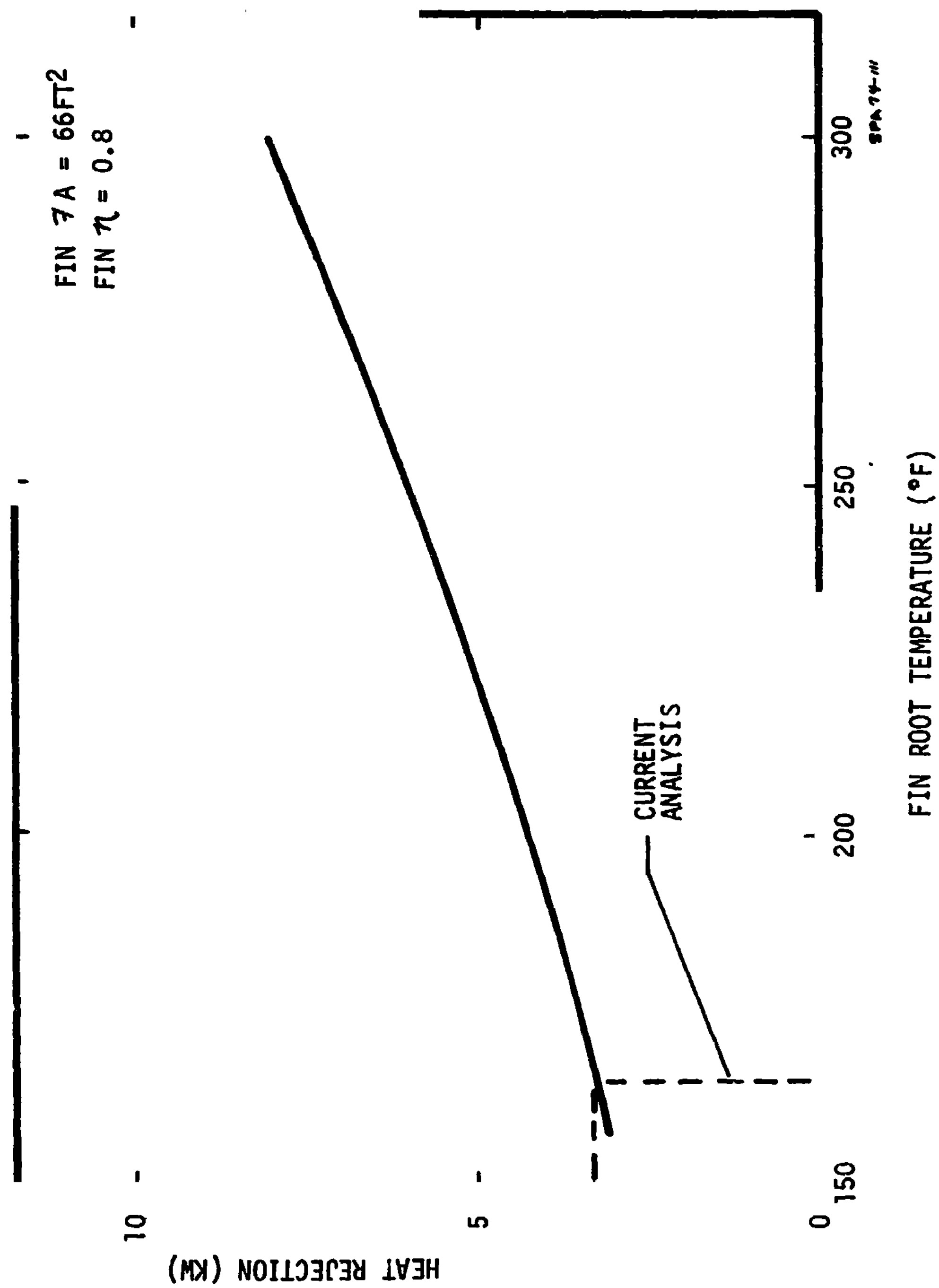


Figure 15. Radiator Heat Rejection

structure temperature of 100°F approximately 6 KW of thermal heat leak can be generated. This is equivalent to 245 pounds of phase-change material on line for one hour. Another means of reducing the capacitor mass requirement would be to use a material with a higher Btu/lb rating. Materials are in existance with values as high as 120 to 130 Btu/lb that change phase in the 150°F temperature range. However, all the characteristics of these materials have not been thoroughly studied to date.

Further definition of equipment to be included in the PHRK (notably electronics) may allow the radiator to operate at higher temperatures. The heat rejection as a function of fin root temperature is shown in Figure 15. If electronic temperatures are allowed to operate at 165°F or above, less thermal capacitor material would be required.

3.2.3 Radiator Sizing

The feasibility of providing a heat rejection capability to allow the PHRK to operate at a steady state electrical load of up to 14 KW was investigated. The radiator area requirements were established as a function of the fuel cell stack's coolant exit temperature because the fuel cell's coolant temperature is the principal parameter affecting the area requirements.

To fully validate the system defined herein, further detailed thermal analyses of the radiator heat rejection and evaluation of the coolant loop fluid and pump requirements will be required. In order to achieve a radiator system of high heat rejection density, portions of the coolant loop must operate at temperatures in excess of 370C (700F). This operating temperature level requires high system operating pressures and special considerations for line connections and seals.

3.2.3.1 System Definition

The requirement to provide cooling for up to 14 KW of consumed electrical power results in a radiator heat rejection requirement of up to 23.5 KW. The additional 9.5 KW of thermal energy comes from the fuel cell waste heat as shown in Figure 5 of Section 3.1.2. For the purposes of PHRK radiator sizing, the Pratt and Whiteney fuel cell characteristics were chosen based primarily on the higher coolant exit temperature of the unit. The 14 KW electrical output is made up of two fuel cells operating

Table 8. Power and Heat Rejection Kit Thermal Load Sources

Source	Waste Heat (kW)	Max. Temp. Level [C (F)]
Fuel Cells (2)	9.5	Study Variable
High Temperature Equipment	11.0	427 (800)
High Temperature Electronics	2.0	177 (350)
Low Temperature Electronics	0.5	71 (160)
TCL Pump(s)	0.5	177 (350)

at the 7 KW output level. The electrical output power is supplied to SPA payload equipment and is subsequently rejected as waste heat within the thermal control loop (TCL). For the purpose of TCL definition, the waste heat load sources were assigned as shown in Table 8.

As shown in Table 8, various load sources also have maximum allowable temperature requirements. The allowable temperatures listed in Table 8 were assigned as possible levels for TCL system definition purposes. Considering both the heat load sources and the associated temperature levels, a TCL similar to the schematic shown in Figure 16 is required. The radiator arrangement features three separate radiator sections. The high temperature section provides for rejection of the waste heat from high temperature qualified equipment which provides for a high heat rejection density and also minimizes the radiator area. However, to achieve the high inlet coolant temperature necessary for this radiator requires that a portion of the total flow be diverted through this section of the TCL. Attendant with this necessary lower coolant flow rate will be a large temperature drop across the radiator. The temperature drop is such that achievement of sufficient radiator effectivenss ($\eta \approx 0.6$) will require subsectioning the radiator with radiator and bypass mixing of the coolant.

The second radiator section (moderate temperature) provides for rejection of fuel cell waste heat with a radiator outlet temperature compatible with the fuel cell cooling requirements. Since the area of this radiator is coupled to the fuel cell waste heat rejection and temperature requirements, it becomes the governing radiator for total system radiator area requirements. To minimize the temperature drop in this radiator (necessary for a reasonable effectiveness; $\eta \approx 0.8$) the total system flow is passed through the radiator after being mixed with the effluent from the high temperature radiator.

A third radiator section provides the necessary temperature drop in a portion of the flow to allow cooling of low temperature electronics. The exit coolant from the low temperature electronics heat exchanger is mixed with the outlet of the secondary radiator (moderate temperature) to allow total system flow through the fuel cell heat exchangers.

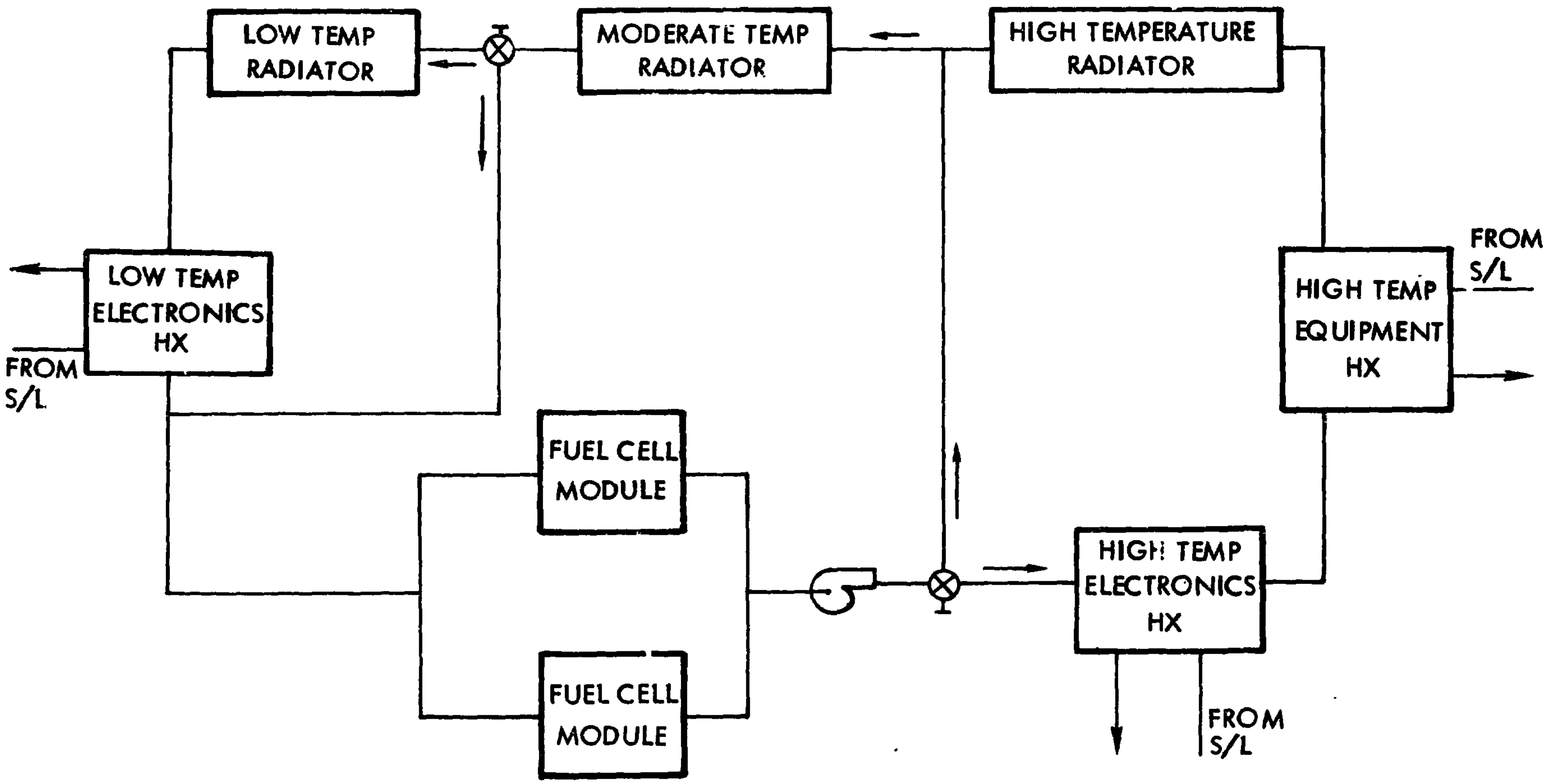


Figure 16. Power and Heat Rejection Kit Thermal Control Loop Schematic

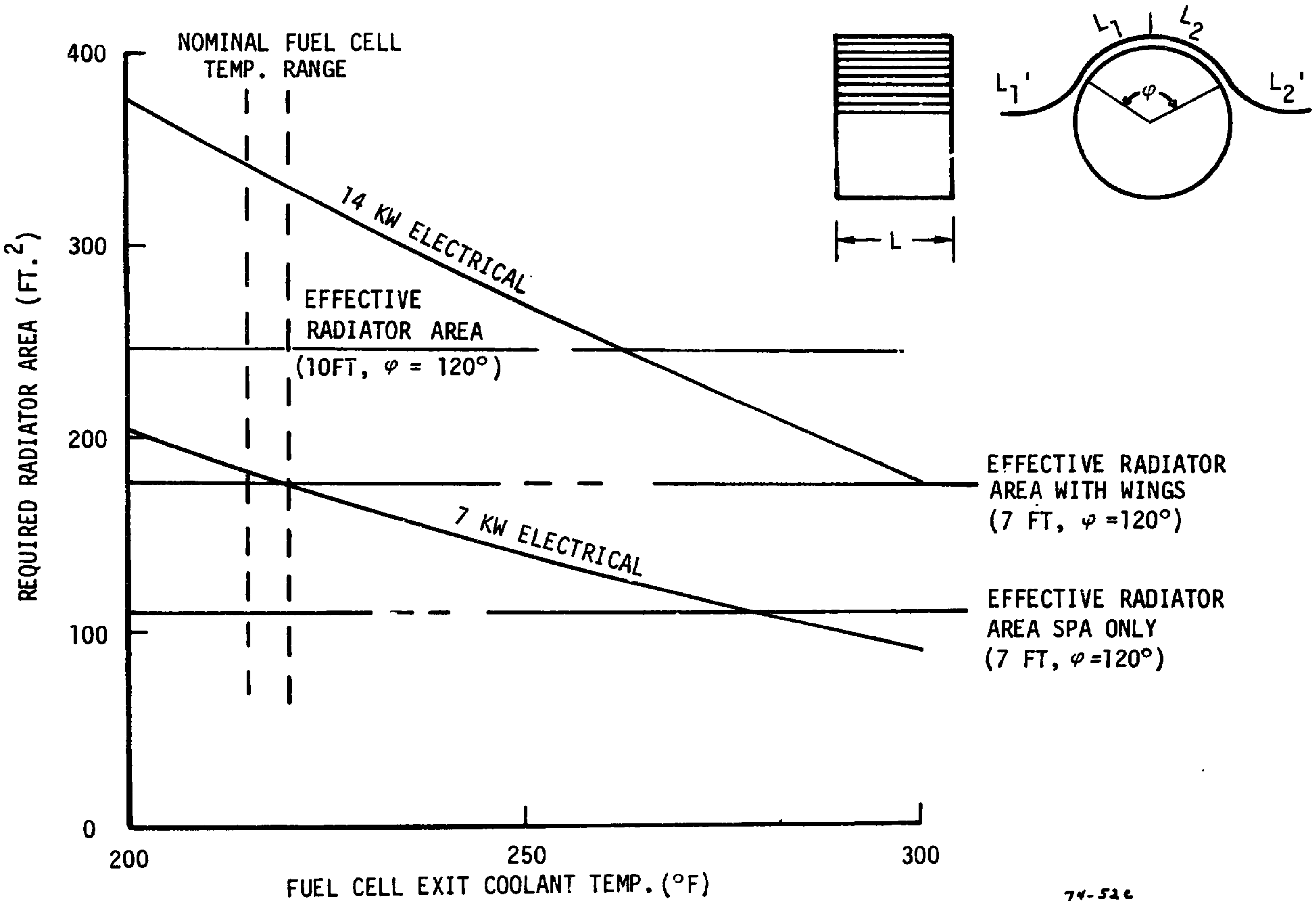


Figure 17. Power and Heat Rejection Kit Heat Rejection Capability

3.2.3.2 System Performance

The total radiator requirement is directly dependent upon the limiting fuel cell operating conditions, specifically the fuel cell coolant exit temperature (Te). As such, the relationship between the fuel cell exit coolant temperature and PHRK radiator area is presented in Figure 17. The required radiator area when compared with the available area shows that the radiator system is limited to only one fuel cell provided the fuel cell can operate at an exit coolant temperature of 140 C (285 F) or higher. The available radiator area is based on the PHRK exposed body surface (120° arc) with a seven-foot-long radiator. A system using a deployed radiator such as shown in Figure 19 could provide for one fuel cell at nominal fuel cell temperature or two fuel cells at an exit coolant temperature of approximately 150 C (300 F). A deployed radiator such as shown in Figure 18 would necessarily require further assessment relative to the effects of shadowing portions of the shuttle radiator system (bay door radiators).

3.2.3.3 System Feasibility

The feasibility of the TCL described herein is predicated on many factors. As shown, major design considerations are the fuel cell's operating conditions and the available radiator area. Referring to Figure 18 and based upon the nominal fuel cell operating temperatures and the defined area for a kit/body-mounted, 120° angle radiator, the output of one fuel cell cannot be accommodated in a steady state mode of operation. For such a radiator size, a fuel cell operating temperature of between 140 C (285 F) to 143 C (290 F) would be required for a one-cell system. Feasibility of operating candidate shuttle-type fuel cells at this temperature level must still be assessed.

Two fuel cells operating continuously requires a substantial increase in either the necessary radiator area or a combination of an increase in radiator area along with an increase in fuel-cell operating temperature. Any increase in radiator area impacts both Shuttle and/or other payload operations and must be assessed accordingly.

Furthermore, the radiator heat rejection effectiveness must be assessed more throughly to validate the conceptual ideas presented. The

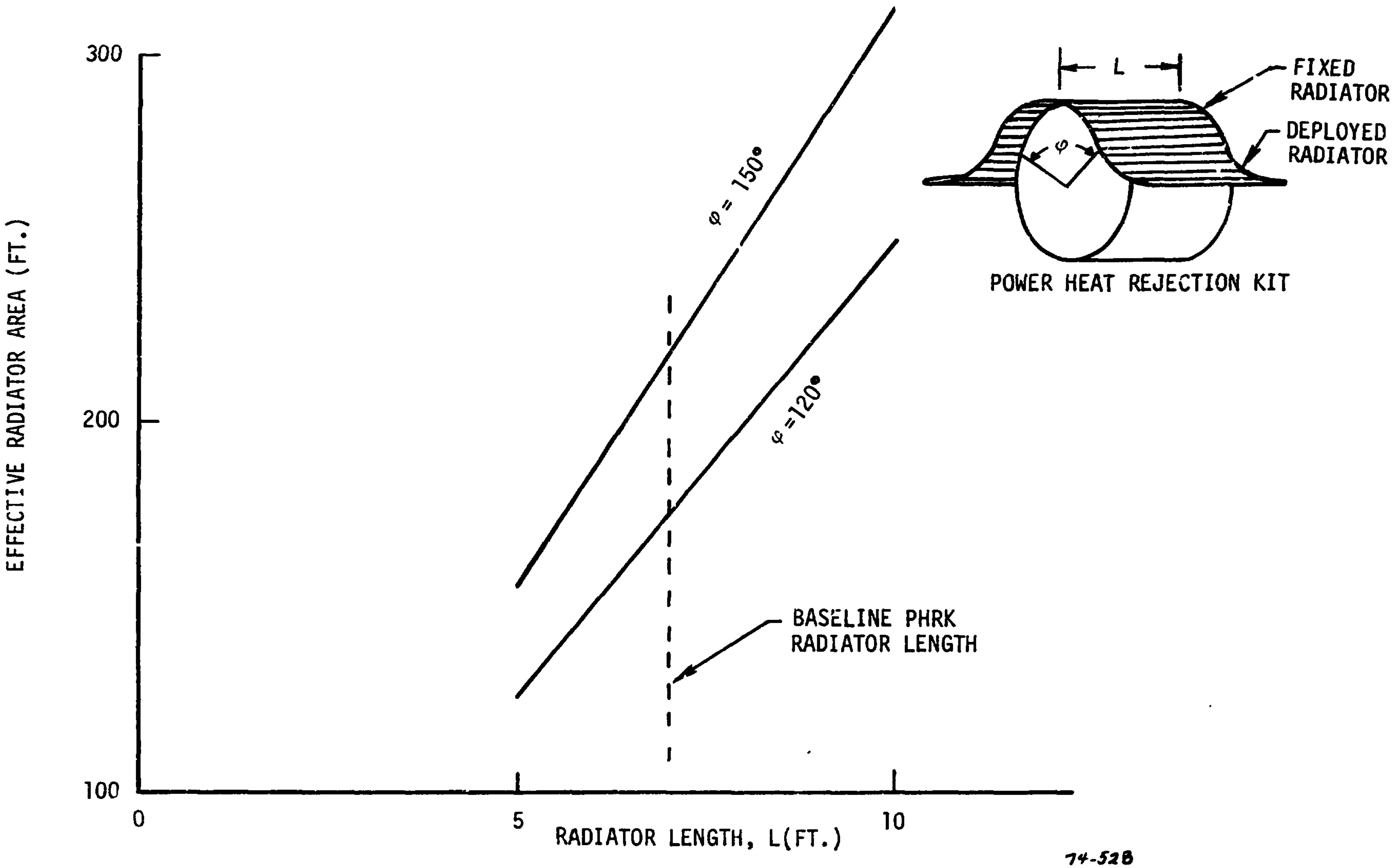


Figure 18 Power and Heat Rejection Kit Deployed Radiator

high temperatures and predicated large temperature drops of these preliminary analyses require that further detailed thermal analysis be conducted to validate overall system feasibility. As such, a coolant fluid assessment must be effected to determine to what degree high temperatures [370 - 427 C (700 - 800 F)] in part of the loop are compatible with existing working fluids. This temperature level is near the upper limit for normally employed coolants. Dowtherm A, for example, is near its operating limit at 400 C (750 F). If a compatible fluid cannot be selected, available fluid temperature limits may become the governing parameter for radiator requirements.

The results of a preliminary system analysis as presented herein indicates that a system to accommodate the output of two fuel cells operating continuously (14 KW) is not out of the realm of possibility; however, impacts to both fuel cell design and shuttle bay radiators may result. Further detailed studies are required before a kit system and its performance ranges can be finalized.

4. CONCEPTUAL KIT DESIGN AND ANALYSIS

4. CONCEPTUAL KIT DESIGN AND ANALYSIS

As a prelude to the activity of preparing conceptual layouts of various accommodation modes for the Power/Heat Rejection Kit, a summary was prepared of weights and volumes for both the experimental and subsystems apparatus. This summary included values for an all-inclusive system as well as an austere version, in order to show the complete spectrum of possible values, and is included in Table 9.

A number of conceptualized SPA power/heat rejection kit packaging layouts are presented in Figures 19 to 29. Configuration 4 as a viable concept has been discounted because of size limitations.

Configuration 6 presents a fuel cell layout in an ERNO pallet configuration.

Table 9. Power-Heat Rejection Kit Nominal Weight/Volume Summary

Experimental Apparatus

Subelements		Complete Weight Kg (lb)	Complete Volume m^3 (ft^3)	Austere Weight kg (lb)	Austere Volume m^3 (ft^3)
Auto Furnace	(F')	476 (1050)	2.65 (90)		
Austere Furnace	(f')			279 (615)	1.84 (65)
Auto Levitation	(L')	1090 (2400)	4.25 (150)		
Austere Levitation	(l')			315 (695)	2.12 (75)
Auto Core	(C')	318 (700)	2.27 (80)		
Austere Core	(c')			281 (620)	1.98 (70)
Combinations					
F' + C'		794 (1750)	4.82 (170)		
f' + c'				560 (1235)	3.82 (135)
L' + C'		1410 (3100)	6.52 (230)		
l' + c'				594 (1310)	3.96 (140)
F' + L' + C'		1880 (4150)	9.07 (320)		
f' + l' + c'				875 (1930)	5.94 (210)

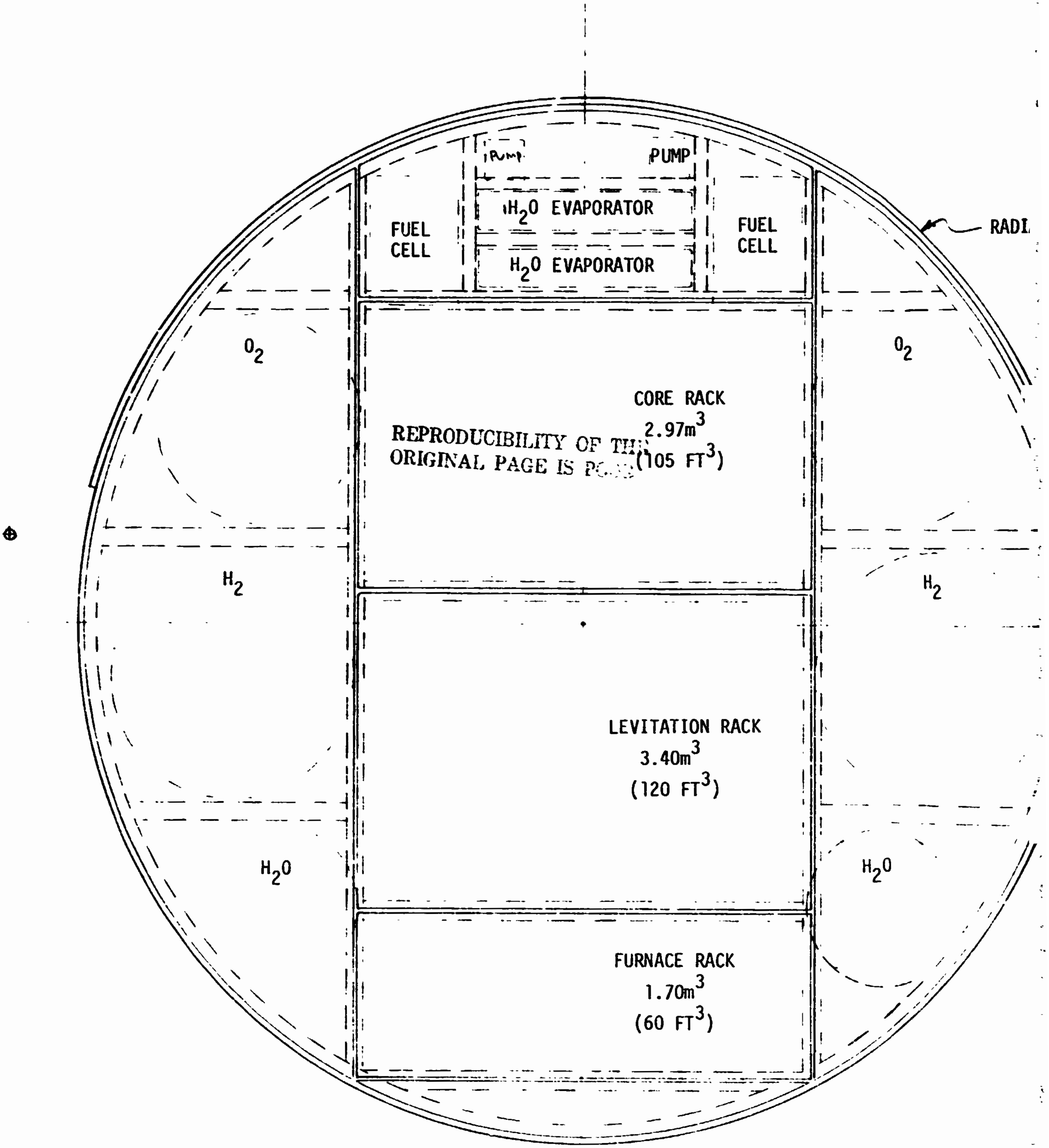
Subsystems' Weights

Power	Complete [*] kg (lb)	Austere [*] kg (lb)
Fuel Cell (GE) w/Controls	[2] 295 (650)	[1] 147 (325)
O_2 Bottles (Dry)	[2] 125 (276)	[1] 63 (138)
H_2 Bottles (Dry)	[2] 88 (194)	[1] 44 (97)
Inverters-400 Hz	[4] 163 (360)	[2] 82 (180)
-1800 Hz	[1] 220 (485)	[1] 220 (485)
TOTALS	891 (1965)	556 (1225)
Thermal		
Radiator	68 (150)	68 (150)
Evaporator/Pumps	181 (400)	181 (400)
Capacitor	227 (500)	
	476 (1050)	249 (550)
Reactants (1 MWH)	454 (1000)	227 (500)
Structure	653 (1440)	653 (1440)

Reconciliations

Subsystems	Complete	Austere
Power	891 (1965)	556 (1225)
Thermal	476 (1050)	249 (550)
Reactants	454 (1000)	227 (500)
Structure	653 (1440)	653 (1440)
	2474 (5455)	1685 (3715)
Apparatus	1880 (4150)	875 (1930)
TOTALS	4354 (9605)	2560 (5645)

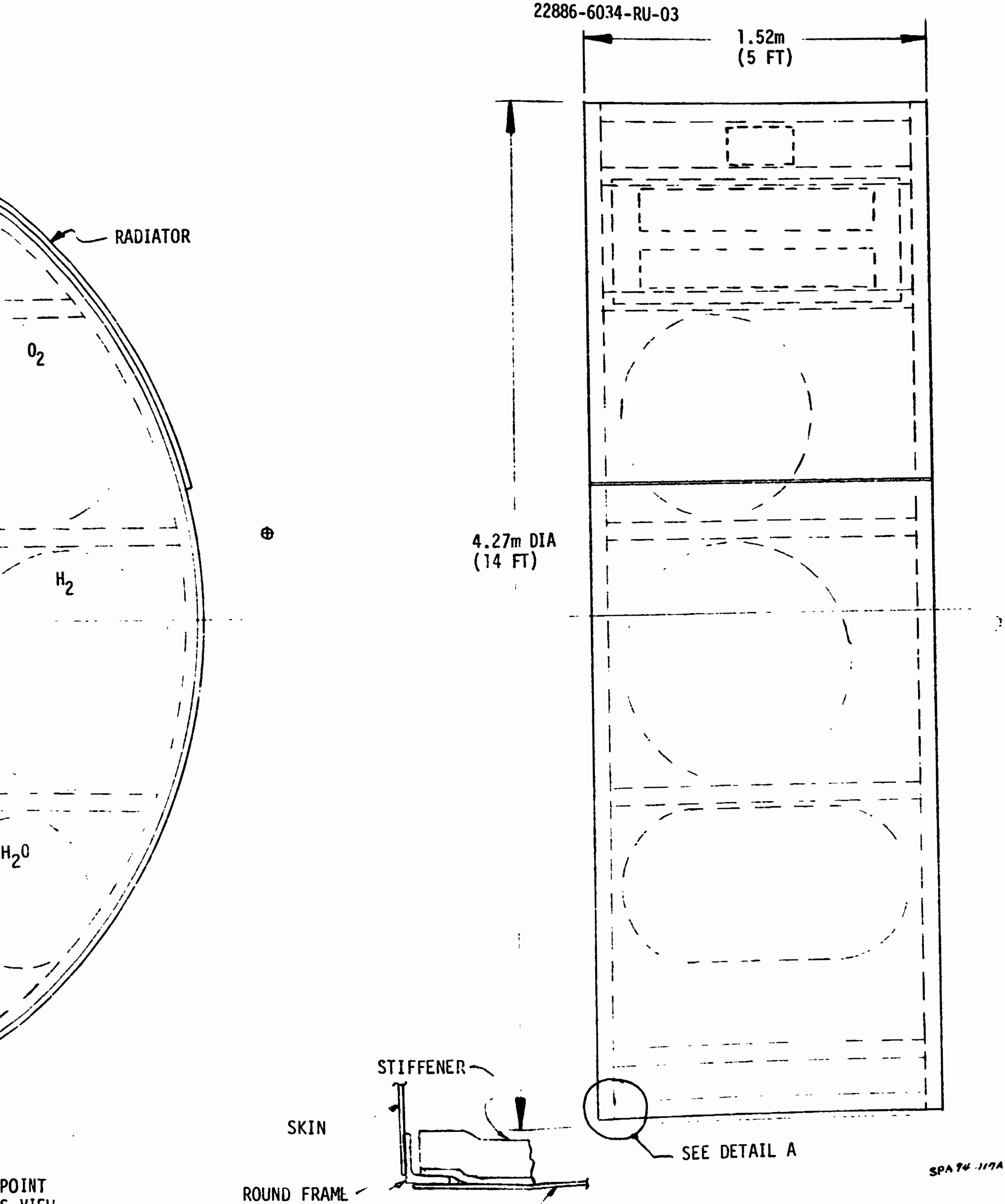
*Number in brackets is that number of items required.



FOLDOUT FRAME

ORBITER ATTACH POINT
3 PLACES IN THIS VIEW

Figure 19. Cross-Sectional Layout Drawing of PHRK - Configuration 1



DETAIL A

ENLARGED & CUT-AWAY

SCALE 1/20

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iguration 1

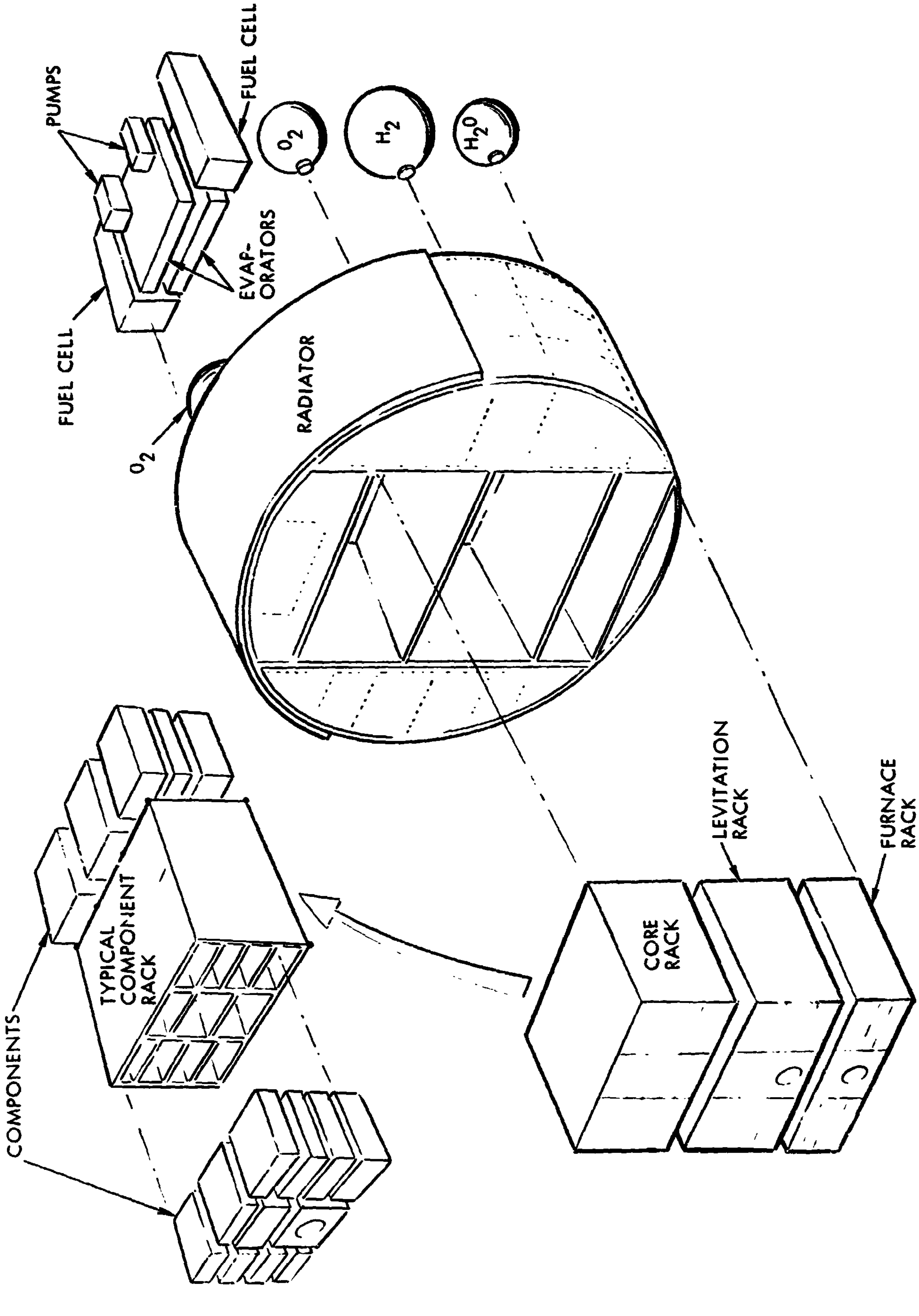

Figure 20. Exploded View of Configuration 1

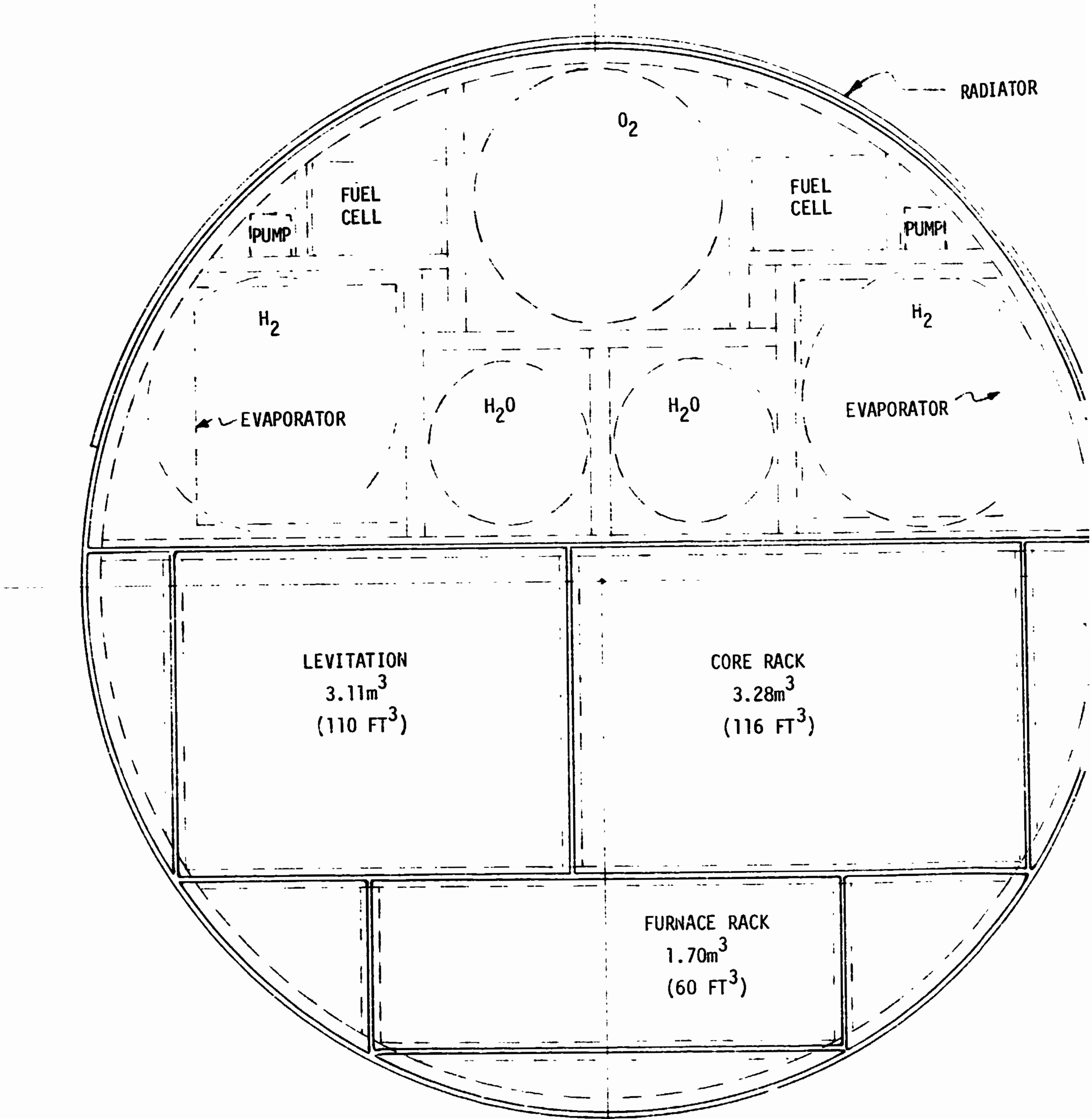

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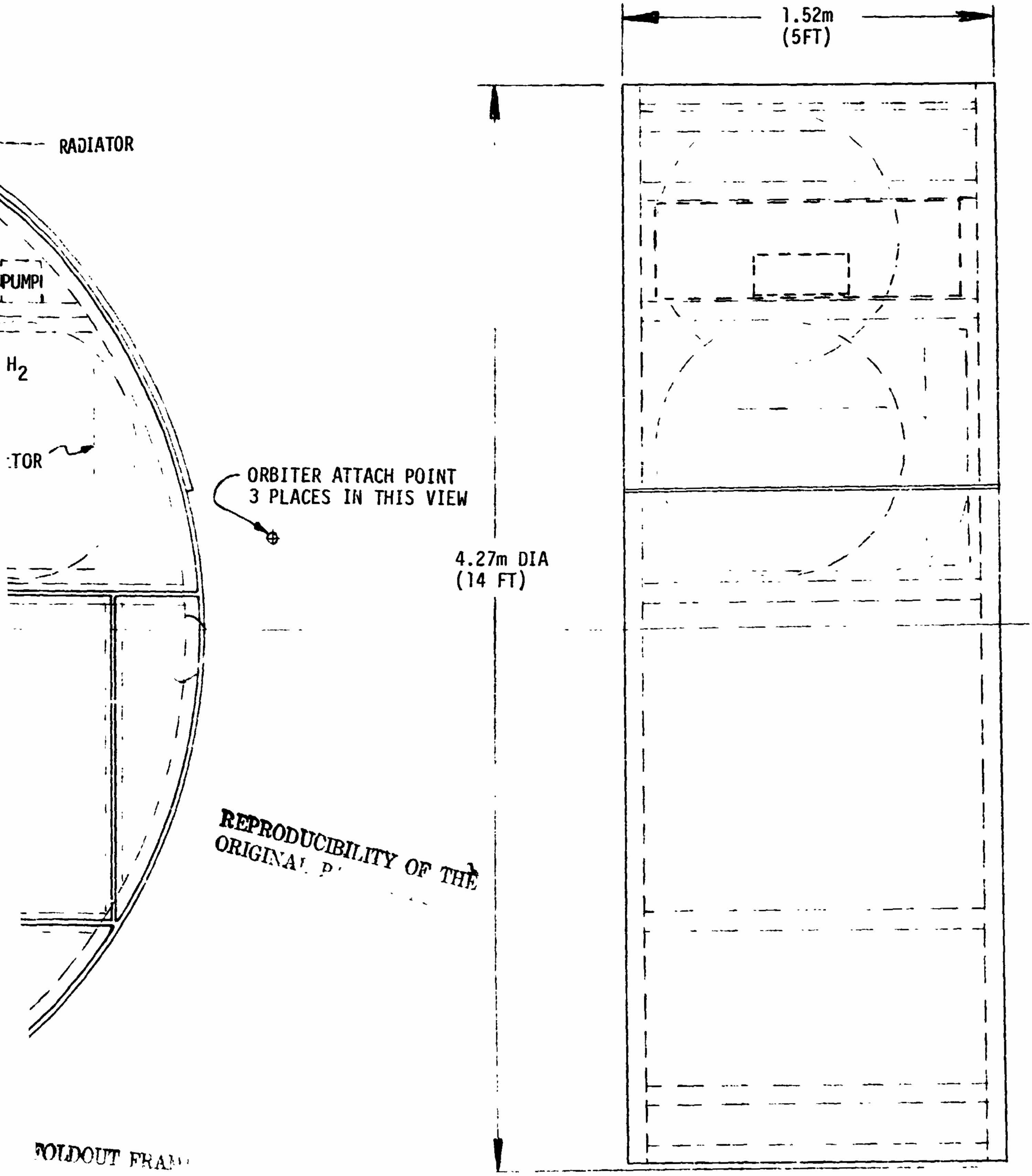
Figure 21. Cross-Sectional Layou



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...ctional Layout Drawing of PHRK - Configuration 2

SCALE 1/20

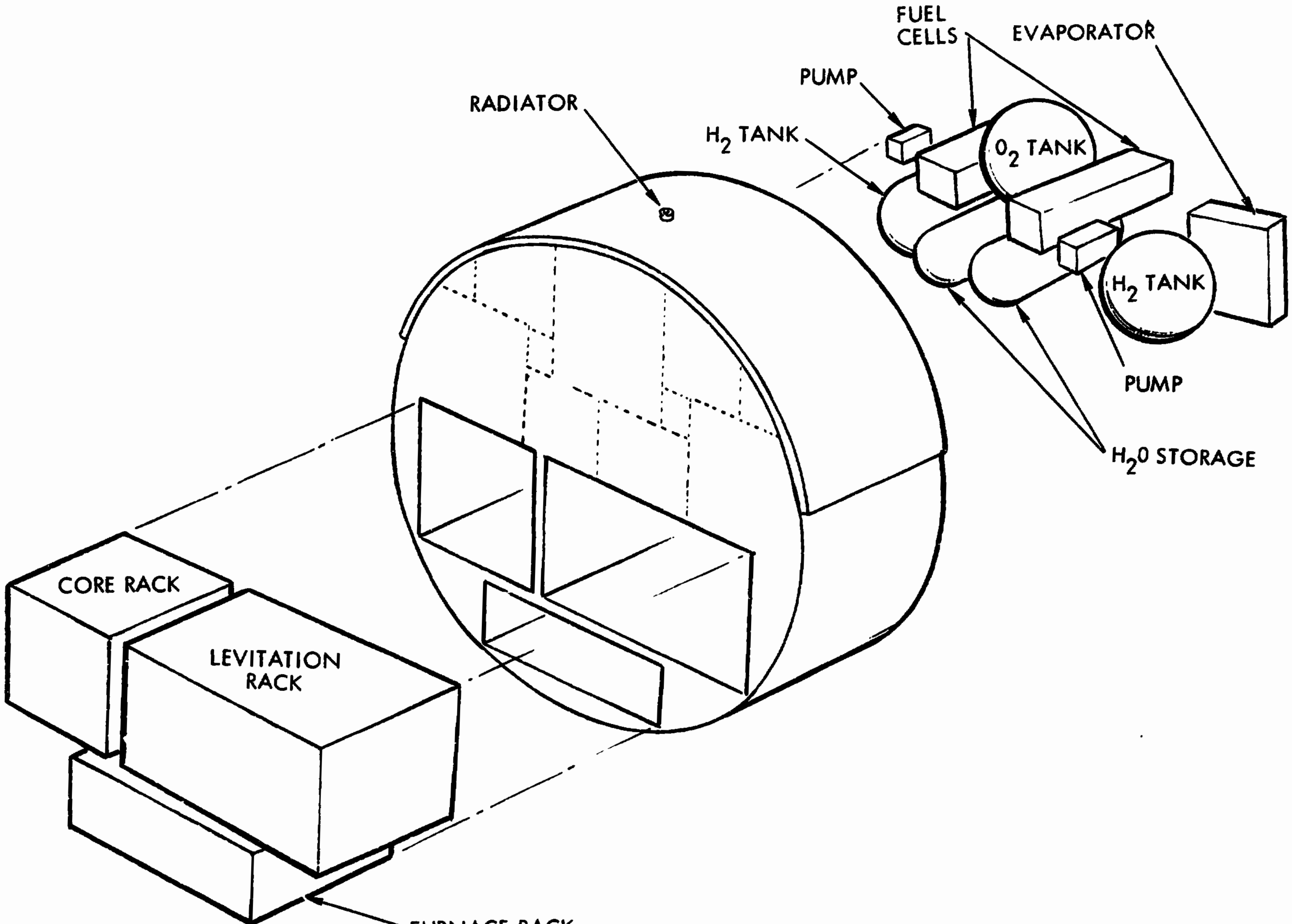
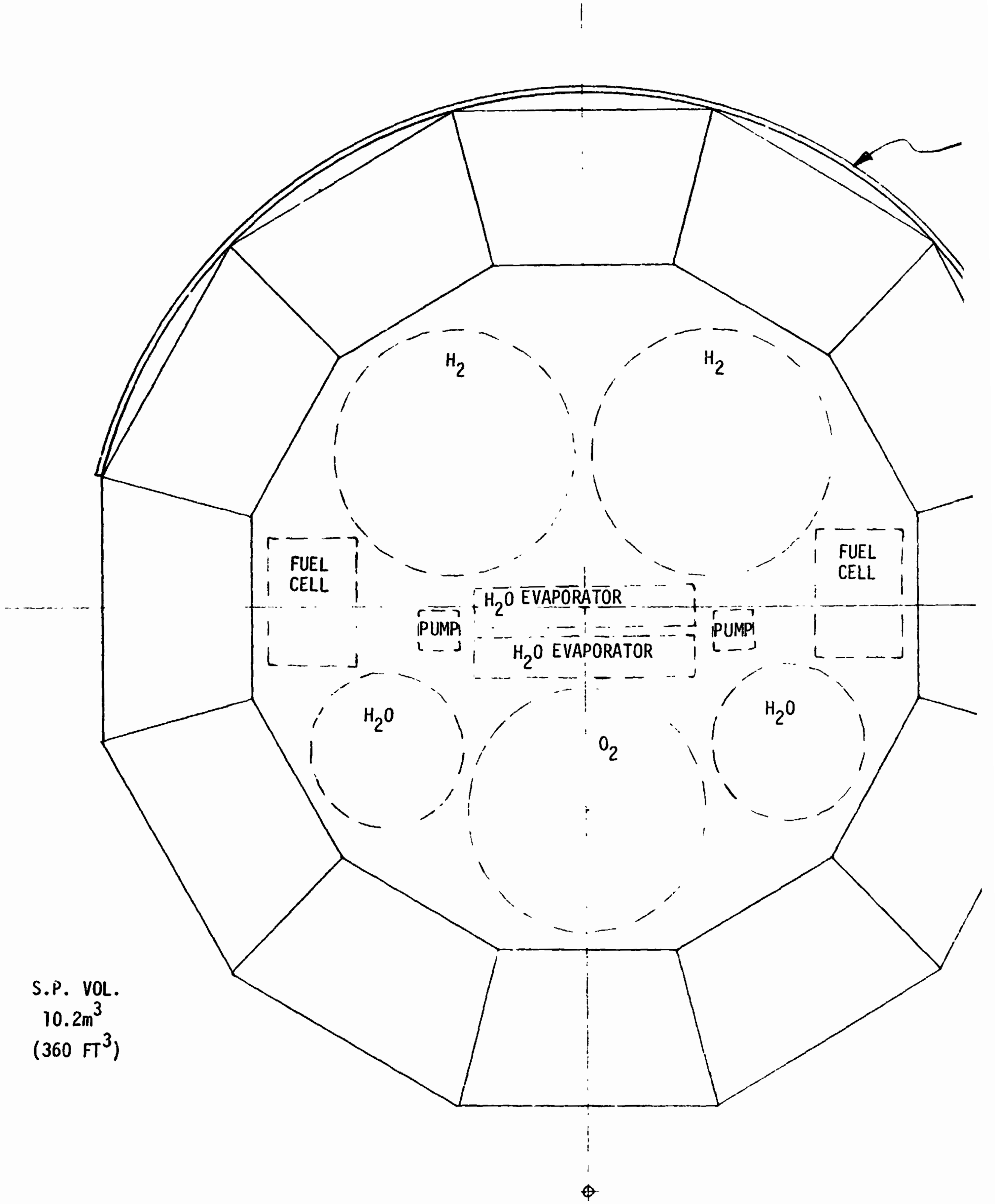


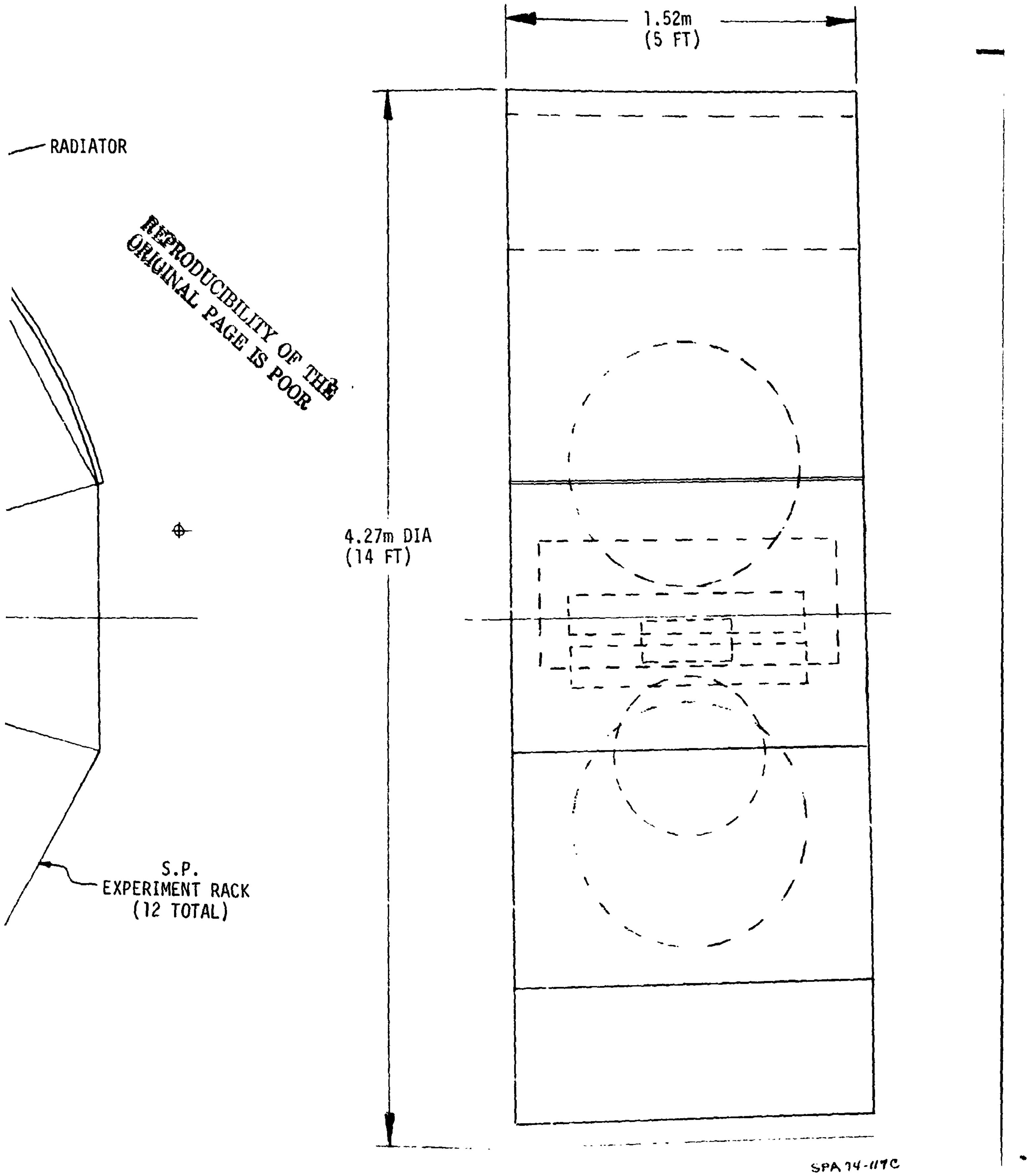
Figure 22. Exploded View of Configuration 2



S.P. VOL.
$10.2 m^3$
($360\ FT^3$)

FOLDOUT FRAME

Figure 23. Cross-Sectional Layout Dr



Drawing of PHRK - Configuration 3

SCALE 1/20

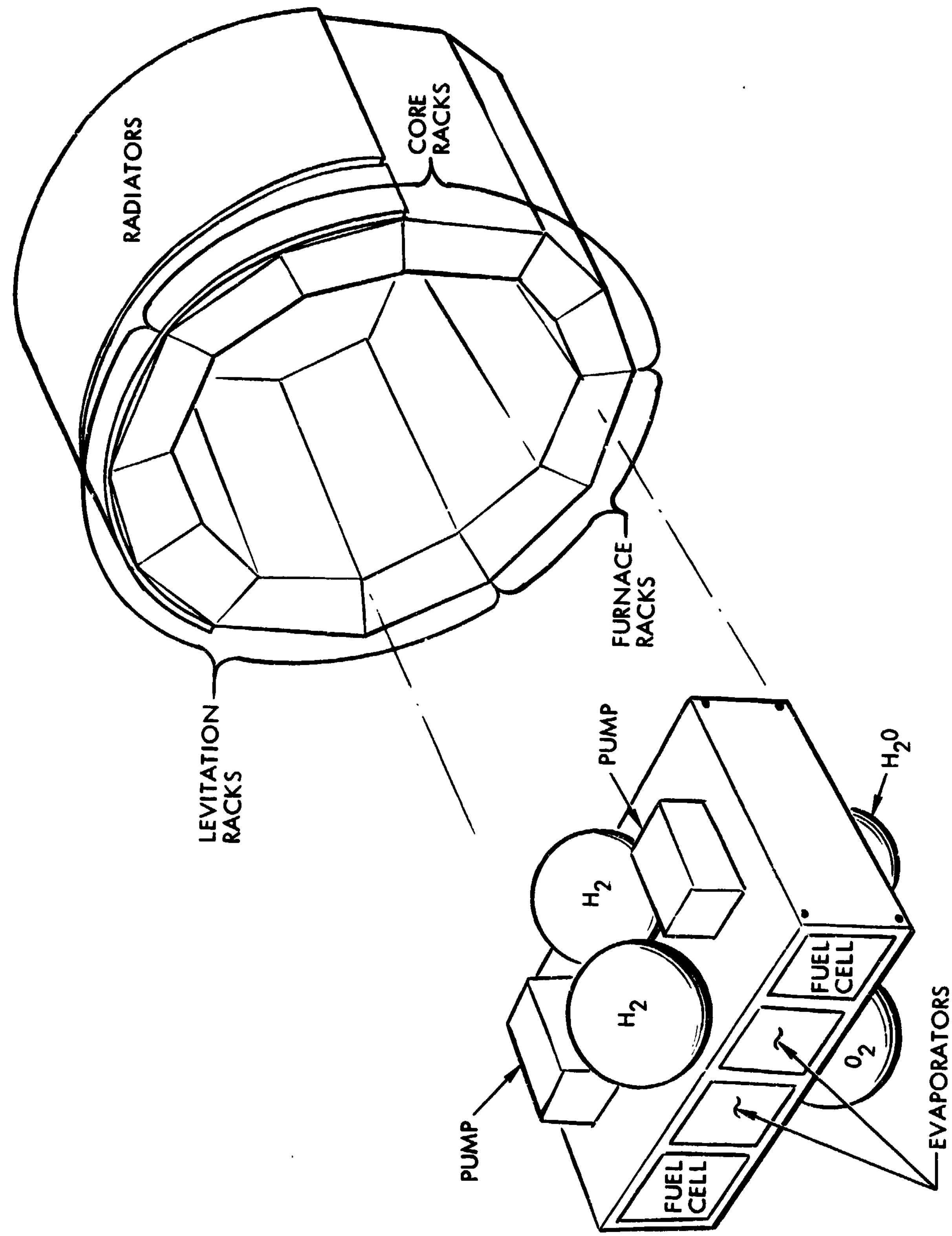


Figure 24. Exploded View of Configuration 3.

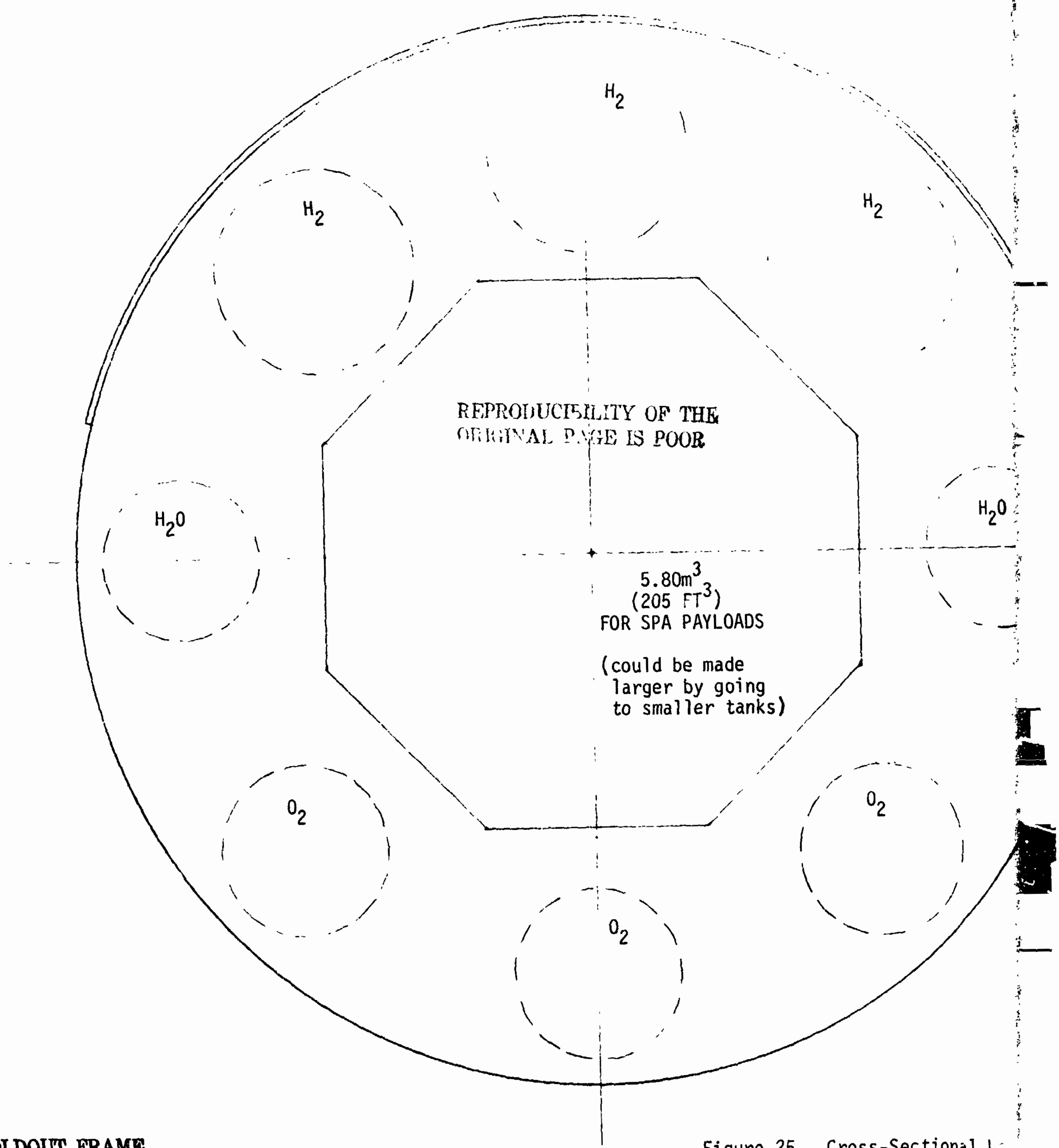


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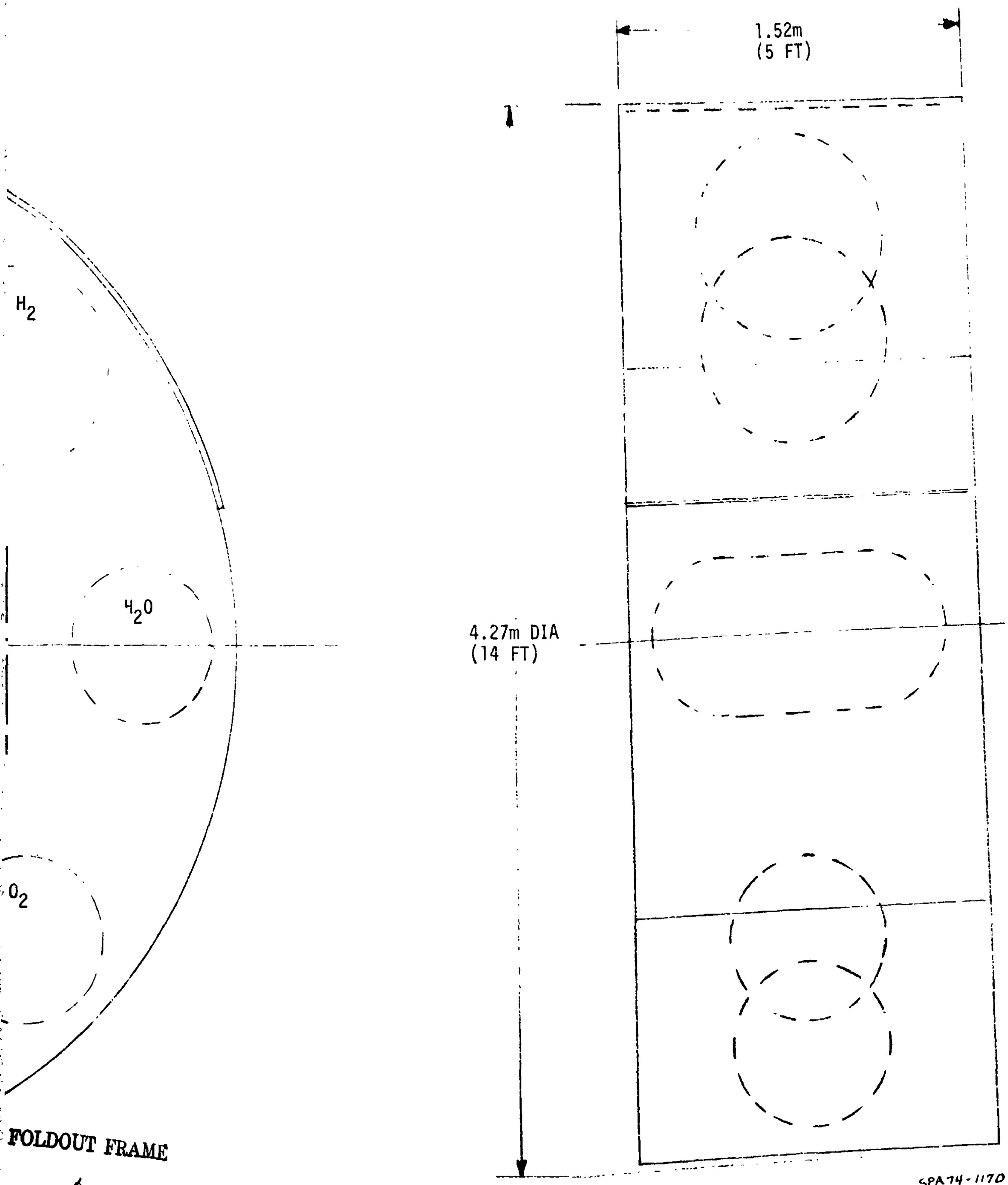
Figure 25. Cross-Sectional La
of PHRK - Configur



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-Sectional Layout Drawing
HRK - Configuration 4

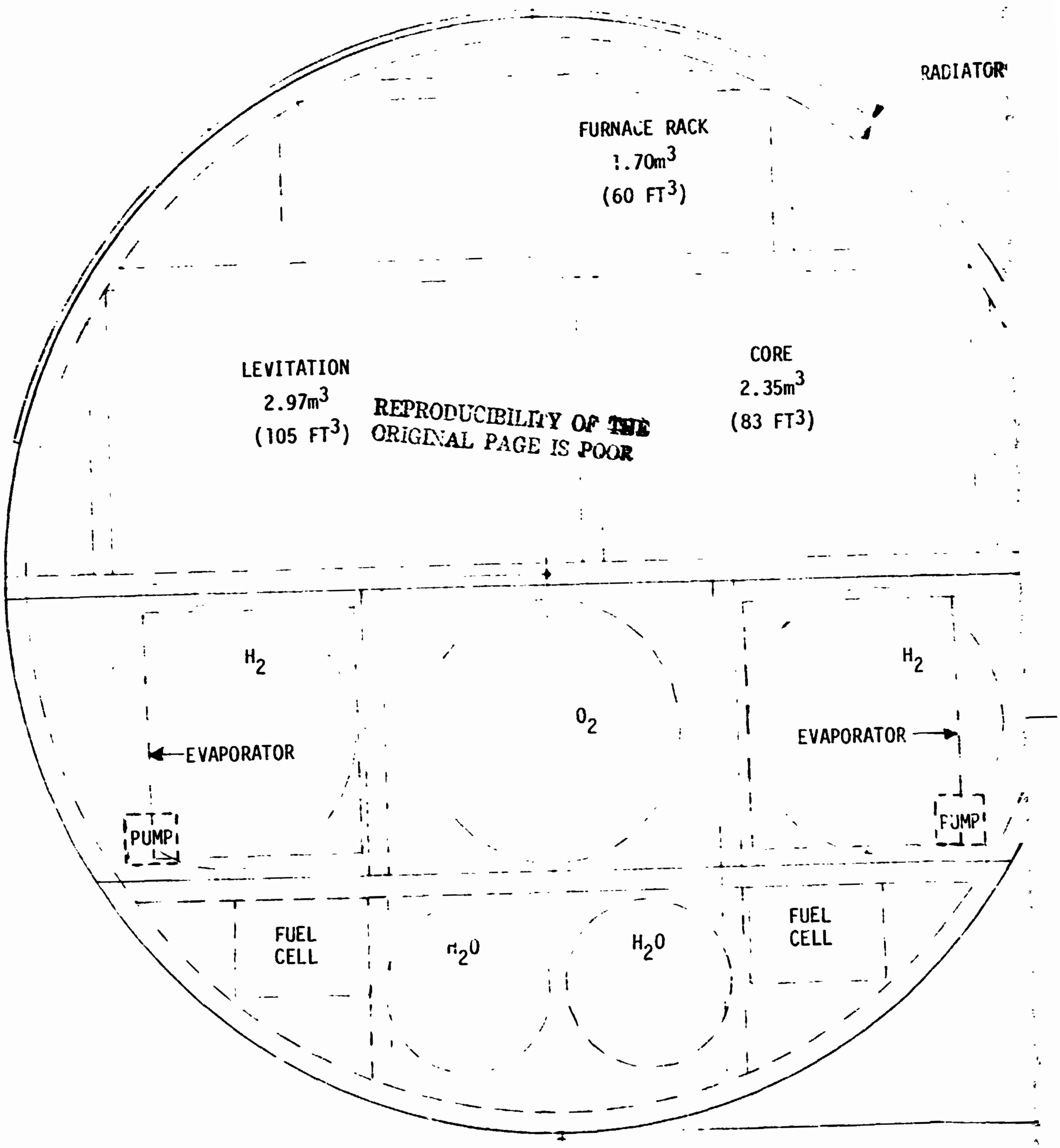

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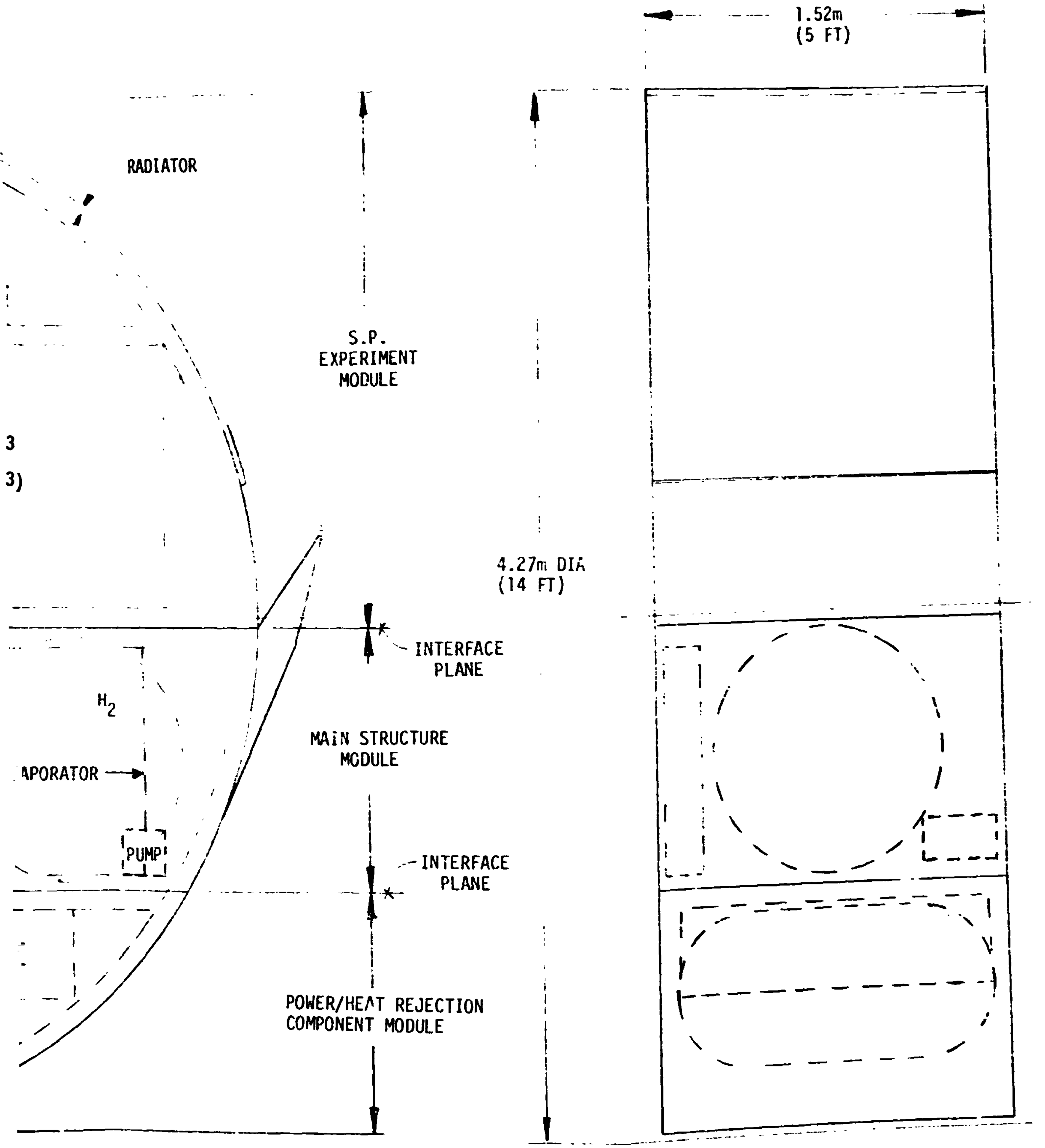
Figure 26. Cross-Sectional La



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oss-Sectional Layout Drawing of PHRK - Configuration 5

SCALE 1/20

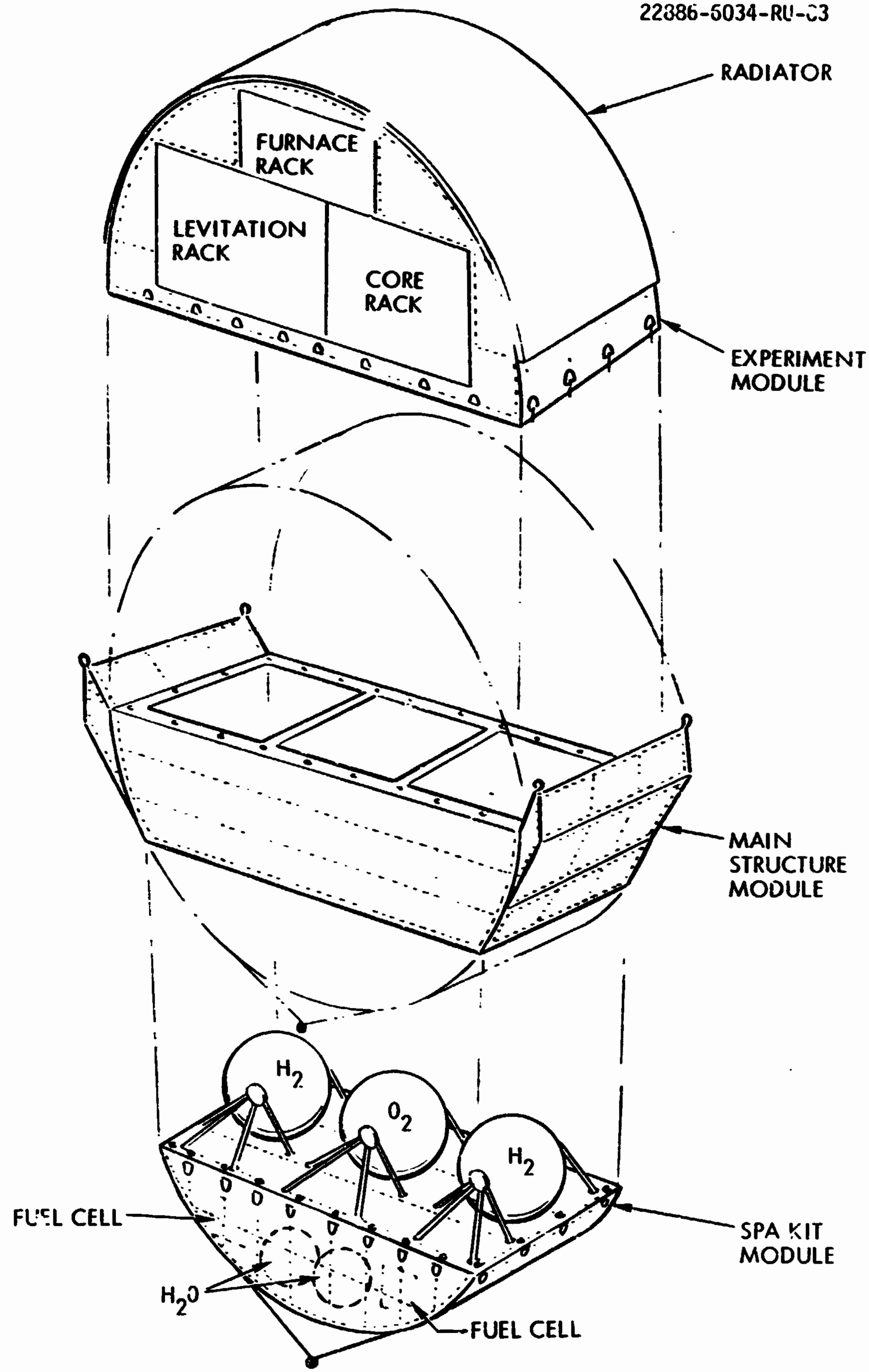


Figure 27. Exploded View of Configuration 5

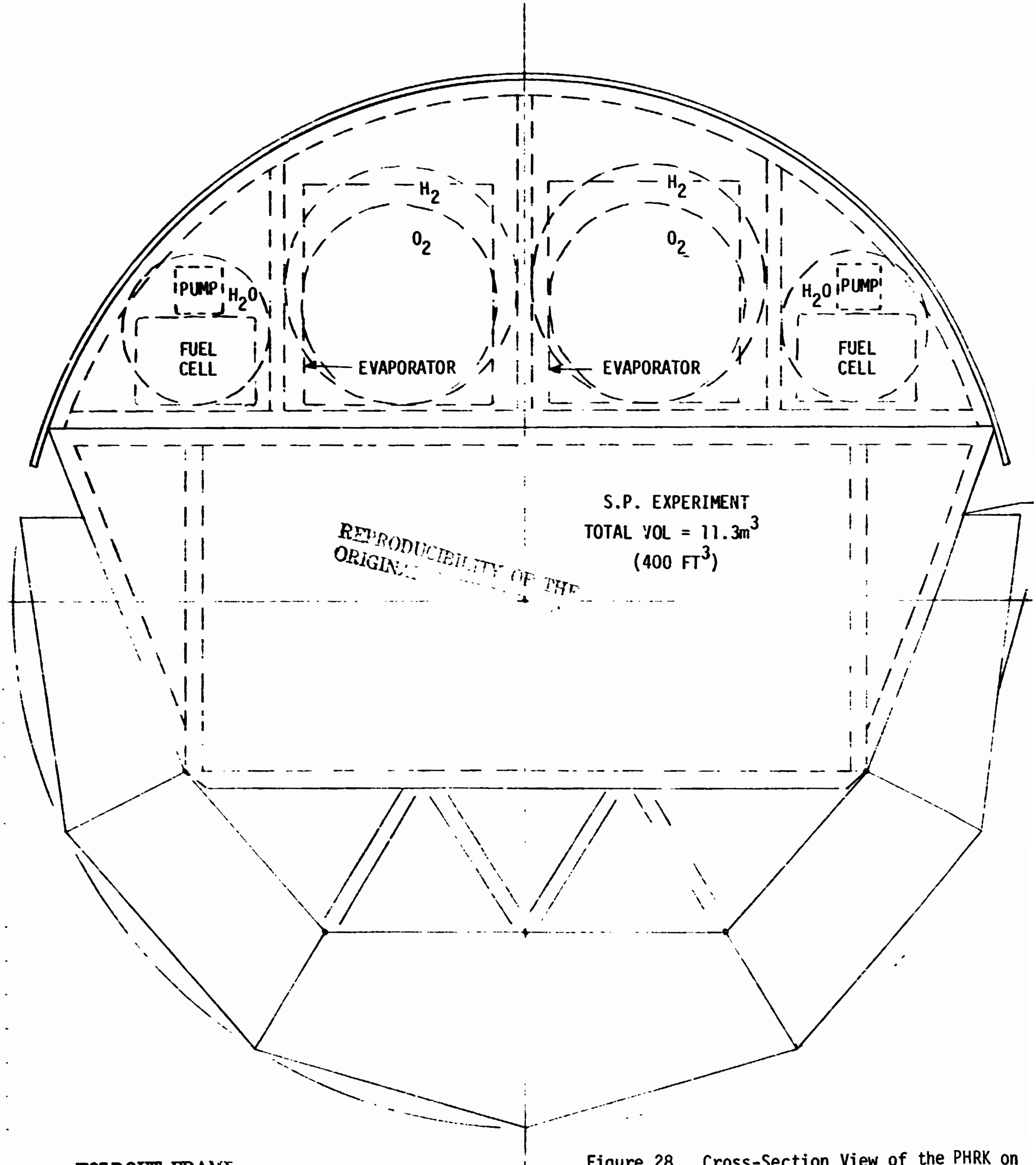
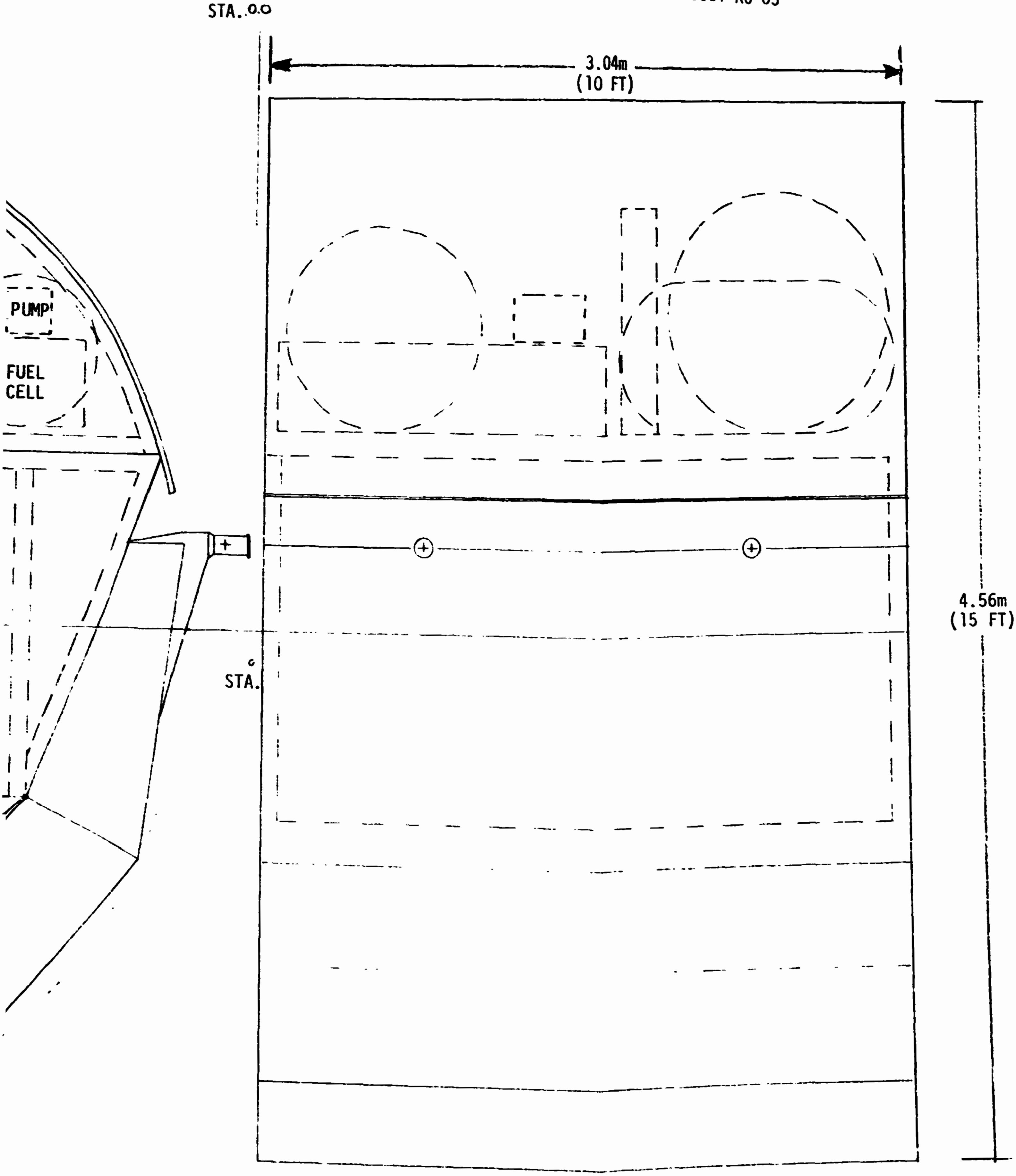


Figure 28. Cross-Section View of the PHRK on Supporting Structure.



ew of the PHRK on an ERNO Cargo Bay
:ture.

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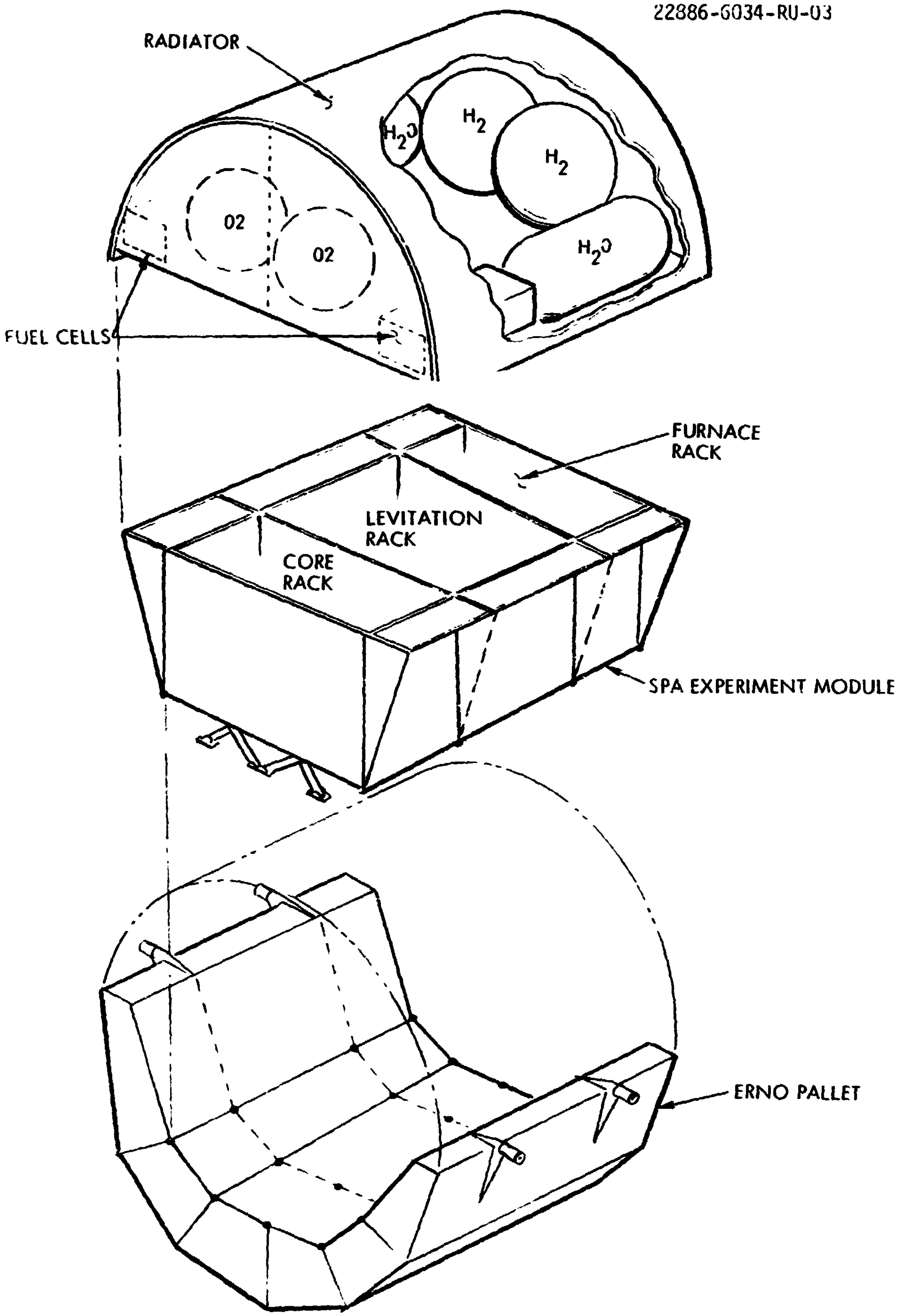


Figure 29. Exploded View of ERNO Configuration

5. WORKING NOTES/
ACCOMMODATION ANALYSIS/
CONCEPT NO. 3

5. ACCOMMODATION ANALYSIS OF CONFIGURATION 3

From among the six different configurations of the PHRK and SPA automated payloads, as shown in Section 4, one was chosen for further accommodation analysis -- Configuration 3. The first step was the selection of the proper storage tanks for the working fluids to be used in the PHRK. The three types of fluids to be used and accommodated are liquid oxygen, liquid hydrogen and water. For each of these fluids, three different tank sizes were considered and evaluated. All were spherical tanks except for one of the water tanks which was a hemispherically ended cylindrical tank. The oxygen tanks considered ranged in size from 67 cm (26.3 in.) up to 98 cm (38.6 in.) and the hydrogen tanks ranged from 81 cm (31.7 in.) to 117 cm (46 in.). The ones chosen for analysis were 84 cm (33 in.) and 99 cm (39 in.) in diameter, respectively. The choices for water storage included a hemispherically ended cylindrical tank, 64 cm (25 in.) in diameter and 127 cm (50 in.) in length and two sperical tanks, 67 cm (26.3 in.) and 51 cm (18.0 in.) in diameter, respectively. The larger of the two spherical tanks was chosen for this analysis. Table 10 presents all of the applicable information on the nine different tanks. The diameters of the tanks are for the total tank envelope which includes any insulation; therefore, the volume-per-tank values are not directly calculable from the diameters. These volumes are internal values. The fluid weights obtained are derived by multiplying the tank volume by the following fluid densities:

	kg/m^3	lb/ft^3
Oxygen	1130	70.7
Hydrogen	698	43.6
Water	1000	62.4

The total weights and volumes of the three selected tanks and fluids are shown in Table 11 along with the values used for the fuel cells, inverters, thermal capacitor and pumps. The volumes obtained are derived from the diameters of Table 10 and are, therefore, representative of the entire tankage envelope not the internally available volumes.

A loads' analysis was performed along with the preparation of drawings showing the detailed layout of the PHRK and automated SPA payloads.

TABLE 10. SELECTION OF FLUID TANKS FOR POWER/HEAT REJECTION SYSTEM (SUMMARY OF EXISTING TANKS)*

Type of Tank	Selec. No.	Spherical Tank Dia. cm (in.)	Qty. Per Pyld.	Vol. Per Comp. m^3 (ft^3)	Tot. Vol. Per Payload m^3 (ft^3)	Empty Wt. Per Comp. kg (lb)	Fluid Wt. Per Comp. kg (lb)	Tot. Wt. Per Comp. kg (lb)	Tot. Wt. Per Payload kg (lb)	Tot. Fluid Wt/Payload kg (lb)
Oxygen (O_2)	1	98 (38.6)	1	0.35 (12.3)	0.35 (12.3)	105 (232)	388 (855)	493 (1087)	493 (1087)	388 (855)
	2	84 (33)	2	0.23 (8.1)	0.46 (16.2)	63 (138)	260 (575)	323 (713)	646 (1426)	521 (1150)
	3	67 (26.3)	3	0.13 (4.75)	0.41 (14.3)	36 (80)	153 (337)	189 (417)	568 (1251)	459 (1011)
Hydrogen (H_2)	1	117 (46)	1	0.67 (23.5)	0.67 (23.5)	95 (209)	45 (100)	140 (309)	140 (309)	45 (100)
	2	99 (39)	2	0.36 (12.6)	0.71 (25.2)	44 (97)	25 (56)	69 (153)	139 (306)	51 (112)
	3	81 (31.7)	3	0.19 (6.8)	0.58 (20.4)	36 (80)	14 (30)	50 (110)	150 (330)	41 (90)
Water (H_2O)	1	64 (25)**	1	0.30 (10.7)	0.30 (10.7)	100 (225)	302 (665)	403 (890)	403 (890)	302 (665)
	2	67 (26.3)	2	0.15 (5.4)	0.31 (10.8)	9.5 (21)	150 (332)	160 (353)	320 (706)	300 (664)
	3	51 (18.0)	6	0.05 (1.67)	0.28 (10.0)	7.7 (17)	45 (100)	53 (117)	318 (702)	272 (600)

*Tankage considered applicable for packaging analysis.

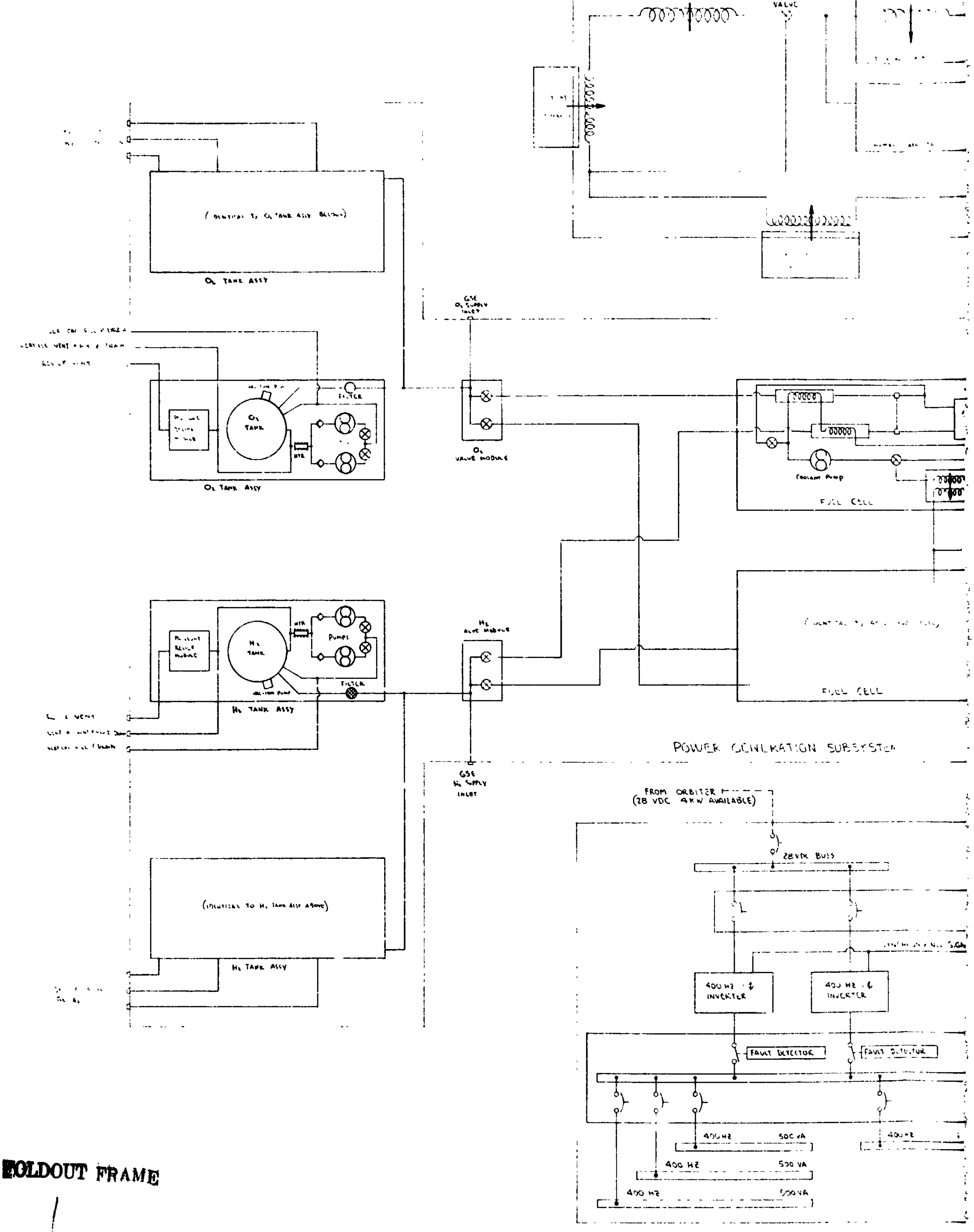
**Hemispherically-ended cylindrical tank, 127 cm (50 in.) in length.

TABLE 11. MAJOR COMPONENT WEIGHTS AND VOLUMES USED IN ACCOMMODATION STUDY OF CONFIGURATION 3

Sub-System	Component	Envel. Vol. Per Comp. M^3 (Ft^3)	Weight Per Comp. Kg (lb)	Qty. Req.	Total Envel. Vol. M^3 (Ft^3)	Total Weight Kg (lb)
Power	Fuel Cell	0.27 (9.4)	147 (325)	2	0.53 (18.8)	295 (650)
	O_2 Tank Assembly (with fluid)	0.31 (10.8)	325 (713)	2	0.61 (21.6)	647 (1426)
	H_2 Tank Assembly (with fluid)	0.51 (17.9)	69 (153)	2	1.01 (35.8)	139 (306)
	Inverters: 1800 Hz	0.45 (16.0)	220 (485)	1	0.45 (16.0)	220 (485)
	400 Hz	0.59 (2.1)	41 (90)	4	0.24 (8.4)	163 (360)
Heat Rejection	Thermal Capacitor	0.14 (5.0)	113 (250)	2	0.28 (10.0)	227 (500)
	Pumps	0.08 (0.3)	-	1	0.08 (0.3)	-
	H_2O Storage	0.15 (5.4)	160 (353)	2	0.31 (10.8)	320 (706)

This was done in order to define the structural weights needed to carry both power and heat rejection equipment and also the weight/volume allocations for the experimental equipment. The working notes of this loads' analysis is presented in the Appendix to this report.

The schematic shown in Figure 30 describes the interfaces between the power, power distribution and thermal subsystems. This provided the basis for the preparation of a drawing showing the PHRK in a modular configuration which is presented in Figure 31. The PHRK module was then conceptually integrated into the cargo bay structure along with the SPA automated payloads (furnace, levitation and core) as shown in Figure 32. The layout follows that of Configuration 3 which was initially presented in Figures 23 and 24 in Section 4.



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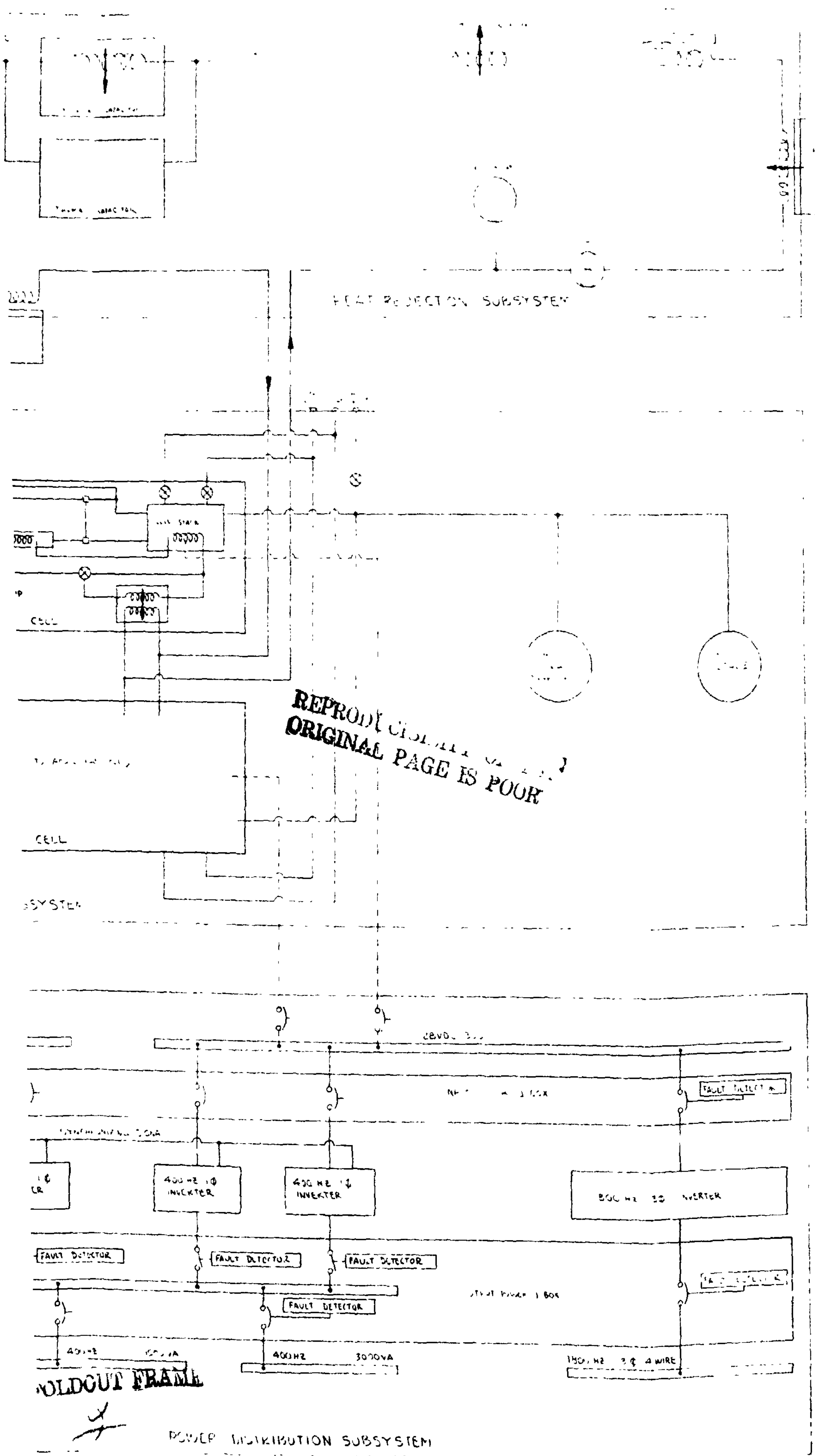
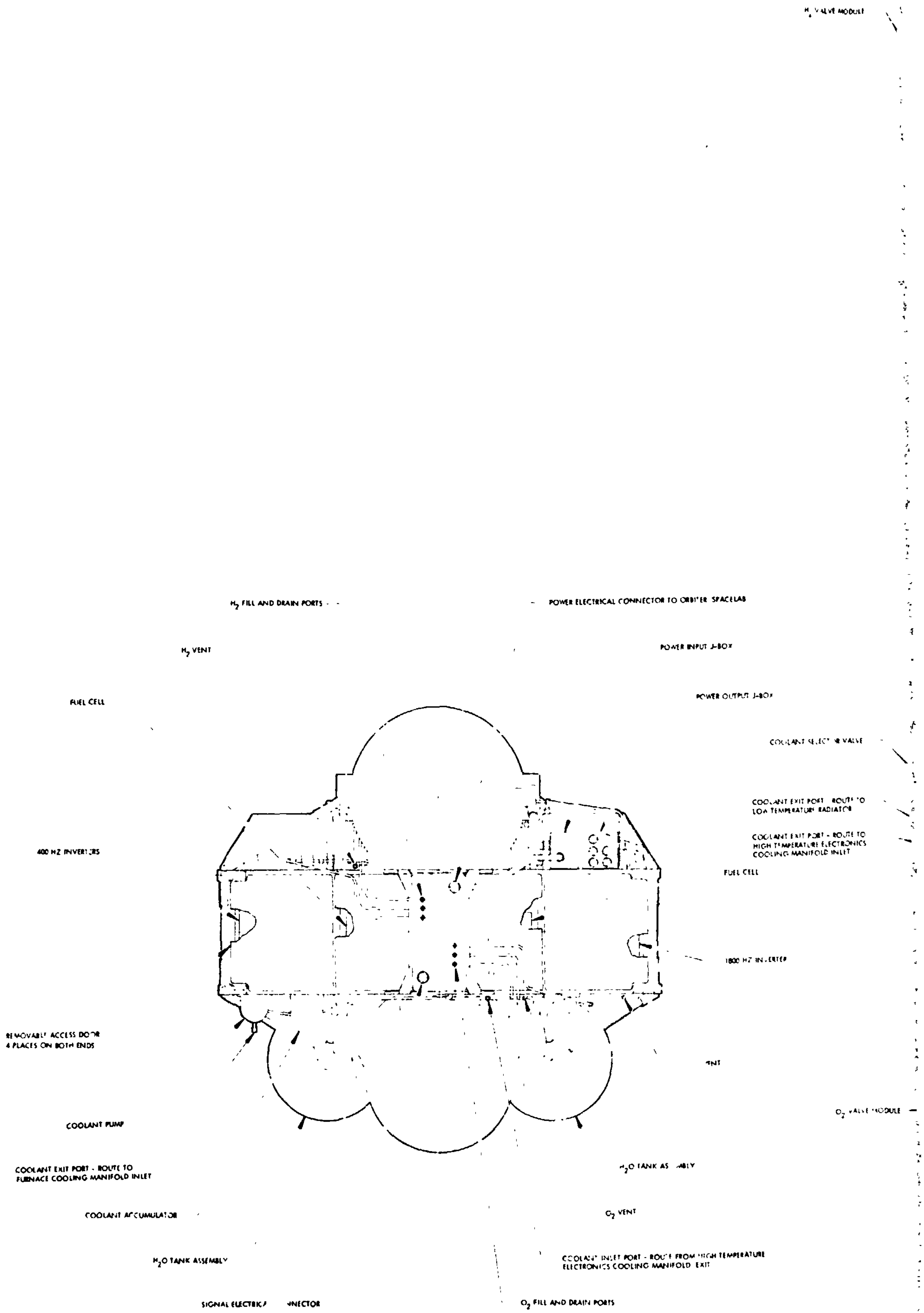
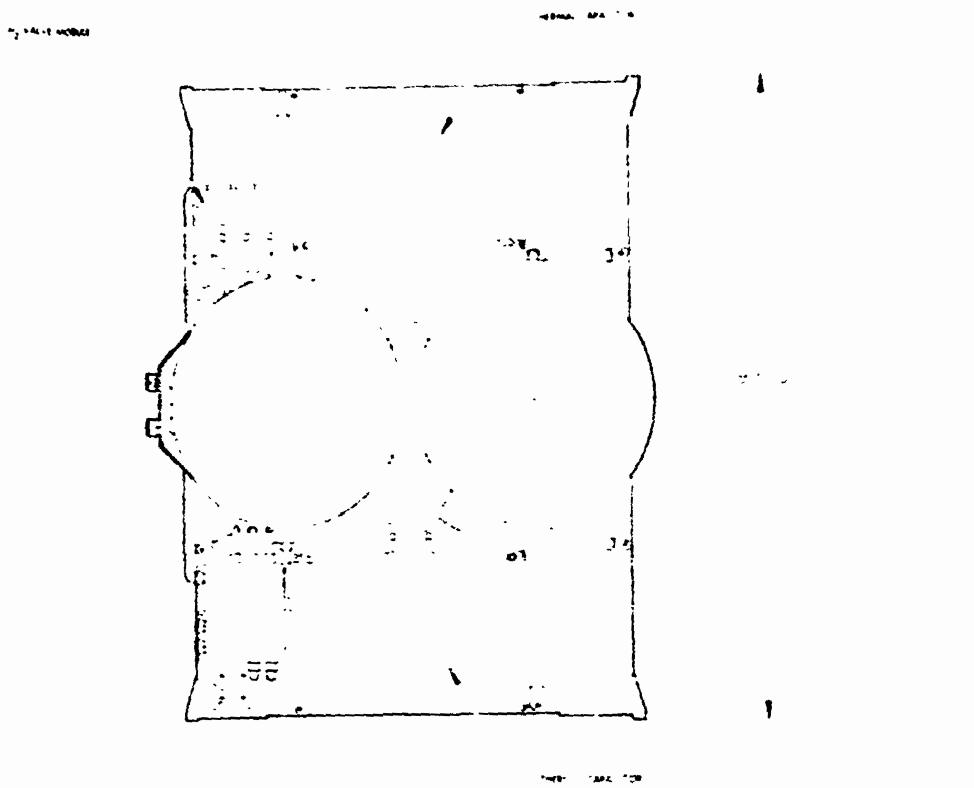


Figure 30. SPA Power Supply/Heat Rejection System Schematic


H_2 VALVE MODULE
H_2 FILL AND DRAIN PORTS
POWER ELECTRICAL CONNECTOR TO ORBITER SPACELAB
H_2 VENT
POWER INPUT J-BOX
FUEL CELL
POWER OUTPUT J-BOX
COOLANT EXIT PORT - ROUTE TO LOW TEMPERATURE RADIATOR
COOLANT EXIT PORT - ROUTE TO HIGH TEMPERATURE ELECTRONICS COOLING MANIFOLD INLET
400 HZ INVERTERS
FUEL CELL
1800 HZ INVERTER
REMOVABLE ACCESS DOOR 4 PLACES ON BOTH ENDS
O_2 VALVE MODULE
COOLANT PUMP
COOLANT EXIT PORT - ROUTE TO FURNACE COOLING MANIFOLD INLET
COOLANT ACCUMULATOR
O_2 VENT
H_2O TANK ASSEMBLY
COOLANT INLET PORT - ROUTE FROM HIGH TEMPERATURE ELECTRONICS COOLING MANIFOLD EXIT
O_2 FILL AND DRAIN PORTS

FRAME



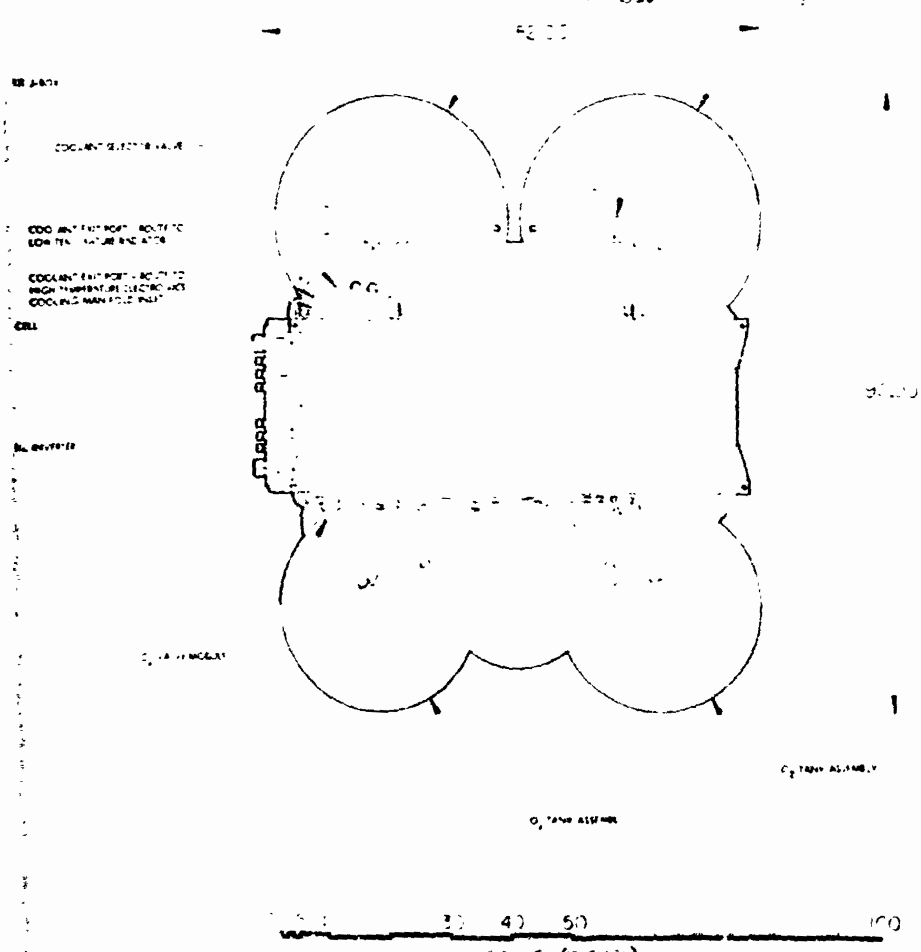


Figure 31. SPA Power Supply/Heat Rejection Module Assembly

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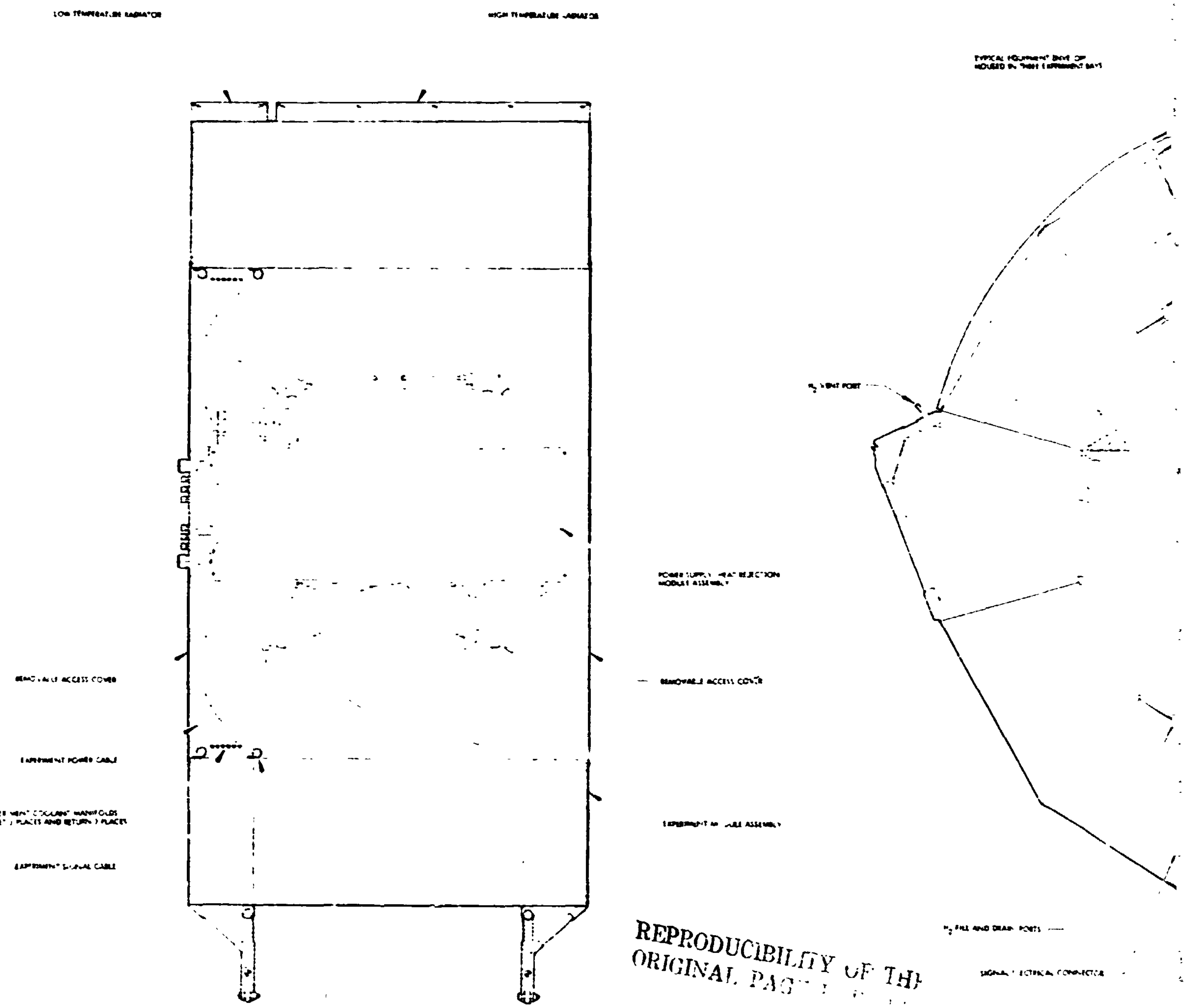
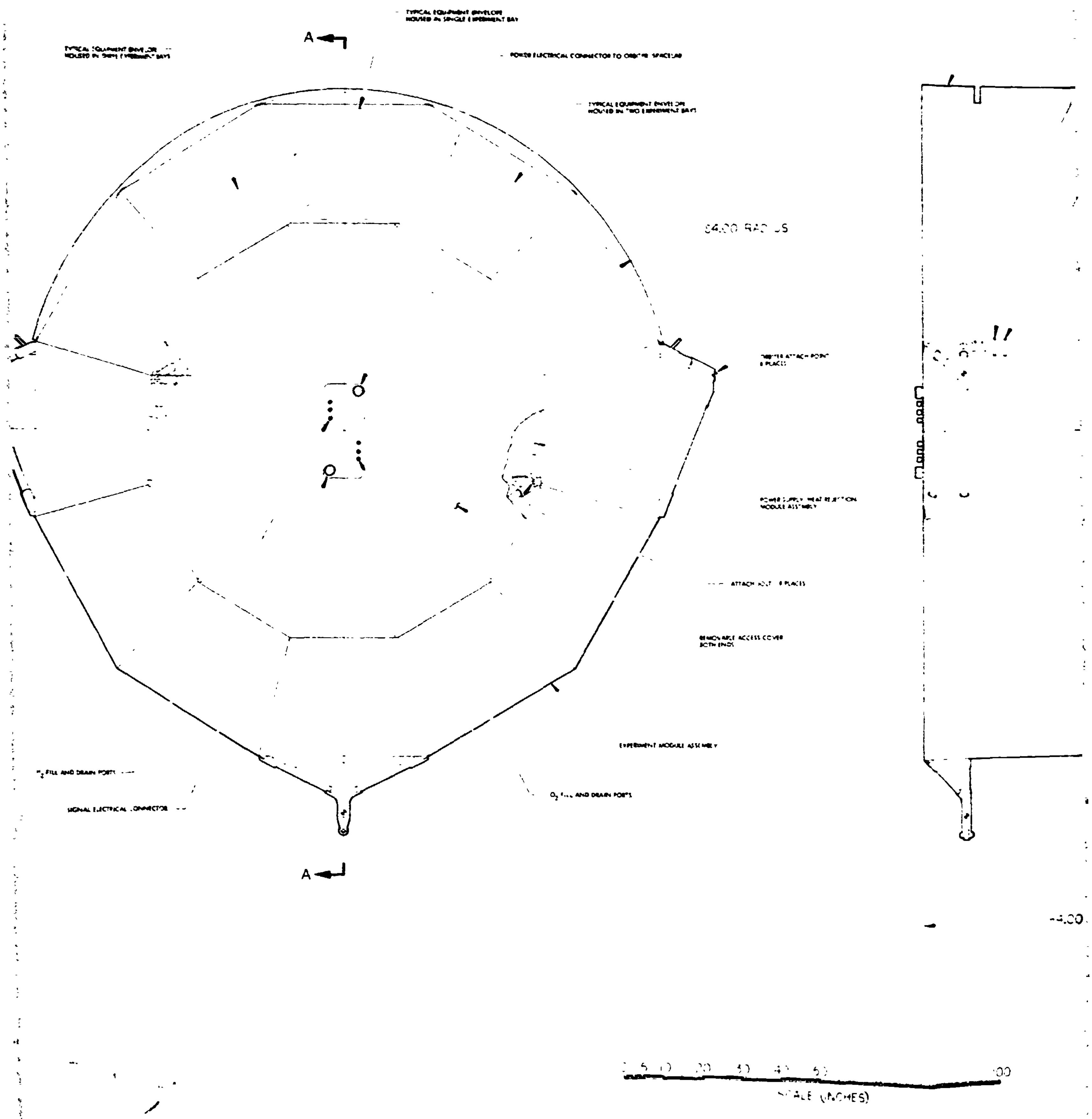


SECTION A-A

FIGURE



A
TYPICAL EQUIPMENT ENVELOPE
HOUSED IN SINGLE EXPERIMENT BAY
SIGNAL ELECTRICAL CONNECTOR
A

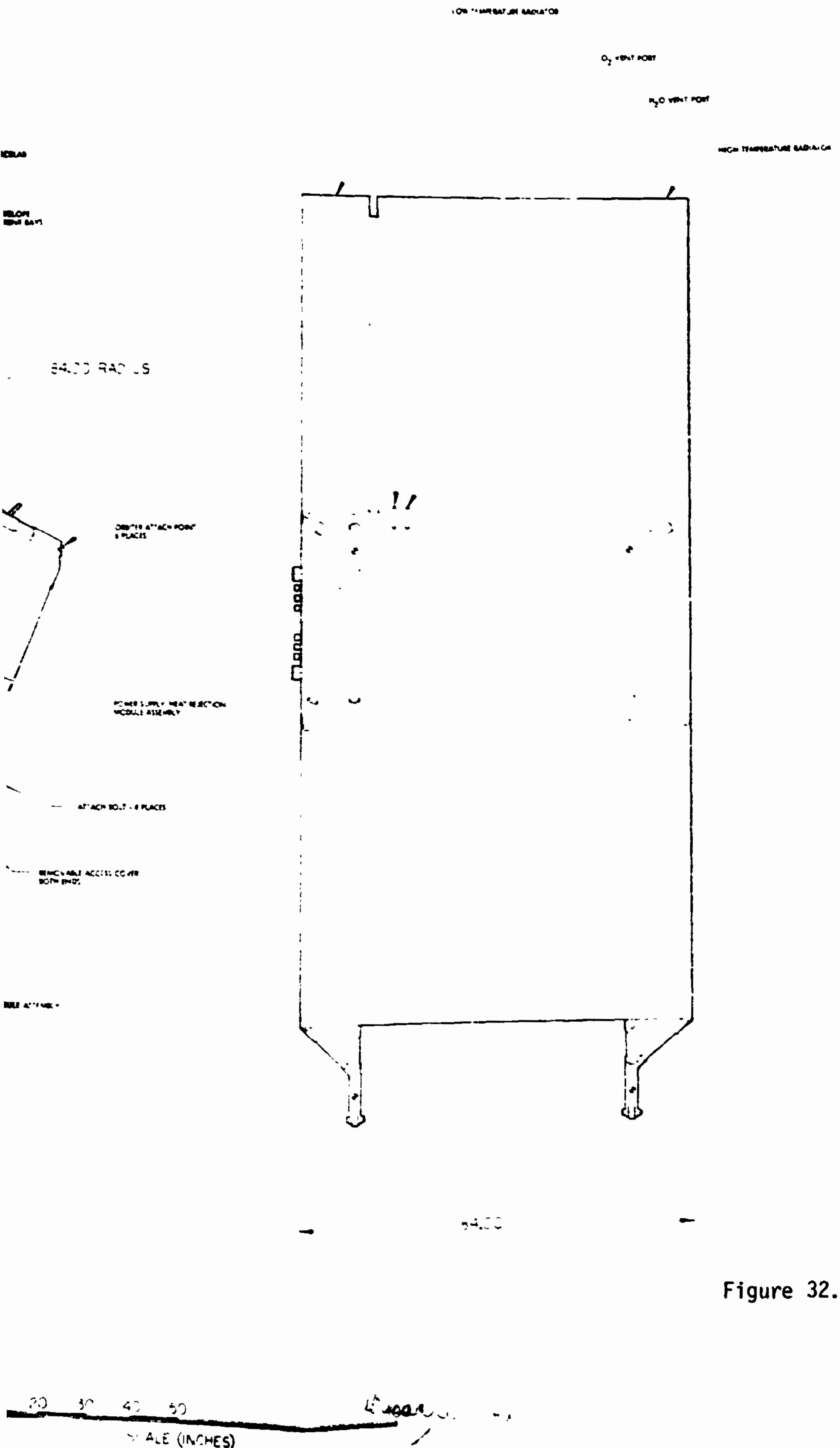


Figure 32. SPA Automated Payload Assembly

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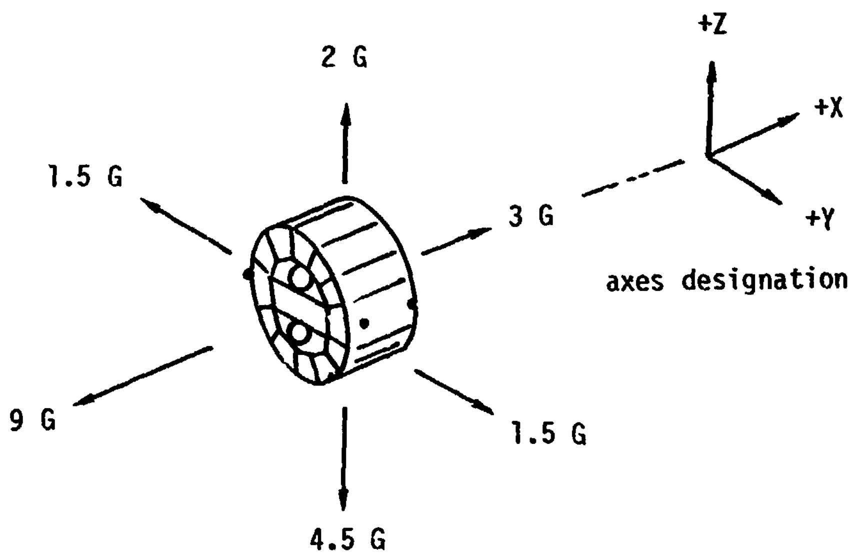
APPENDIX

WEIGHT SUMMARY - SPA AUTOMATED PAYLOAD
(Based on Preliminary Structural Sizing)

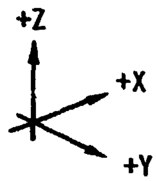
1.	Experiment Structure (Arch Config.)		
	Common Experiment Cell	9 Reqd. X 93 = 837	
	Main Load Carrying/Experiment Cell	3 Reqd. X 122 = 366	
		1203 →	1203 lb.
2.	Power/Heat Rejection Module Structure	→	280 lb.
		Total Structure Weight =	1483 lb.

Structure is typical aircraft type, semi-monocoque, skin stringer construction. Load factors used are shown below (maximum for any given condition).

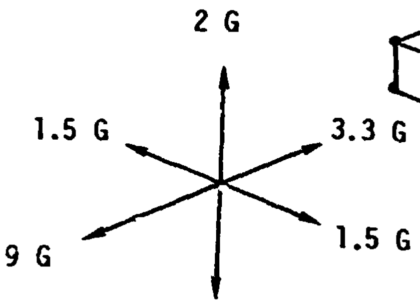


POWER/HEAT REJECTION MODULE
Loads, Stress and Weight

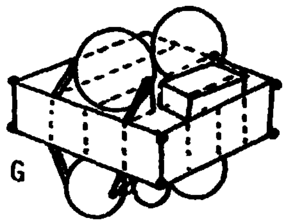
LOAD FACTORS:



(axes)



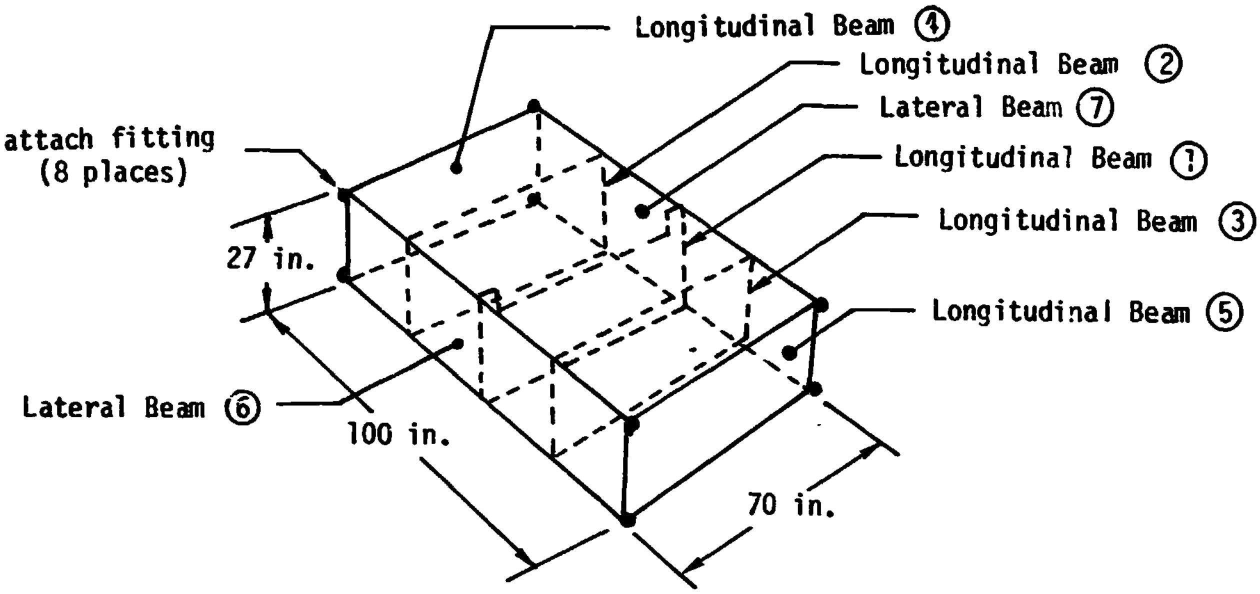
(load factors)


(module)

EQUIPMENT WEIGHTS:

a) Fuel Cells (with controls)	2 x 325 =	650 lb.
b) O_2 Bottles (container and reactant)	2 x 713 =	1426 lb.
c) H_2 Bottles (container and reactant)	2 x 153 =	306 lb.
d) Inverters (4 @ 400 Hz and 1 @ 1800 Hz)	(4 x 90) + (485) =	845 lb.
e) Thermal Capacitor (dived into 2 units)	2 x 250 =	500 lb.
f) H_2O Storage	2 x 353 =	706 lb.
	Total =	4433 lb.
	Structure =	+

STRUCTURAL SIZING: (Close approximation - with conservative approach)



Equipment loads are applied to (5) longitudinal beams which transmit them to (2) lateral beams.

Beam 1 - This beam supports one-half the load, of each of the two fuel cells. 9 G forward and 4.5 G down loads are the worst case.

F.C. Wt. = 325 lb.

$\frac{\text{F.C. Wt.}}{4} = 82$ lb.

4.5 G x 82 x 2 = 138 lb.

$\frac{9 \text{ G} \times 164 \times 10}{40} = 396$ lb.

$$\begin{array}{r} 738 \\ +\ 396 \\ \hline 1134 \end{array} \qquad \begin{array}{r} 738 \\ -\ 396 \\ \hline 342 \end{array} \text{ lb.}$$

$$R1 = \frac{(15 \times 342) + (55 \times 1134)}{70}$$

$$R1 = \frac{5130 + 62370}{70}$$

$$R1 = \frac{67500}{70} = 964 \text{ lb.}$$

R2 = 1134 + 342 - 964 = 512

(a) Webb Thickness - Shear load $\frac{964}{22}$ = 44 lb/ in depth

Skin τ < .010 so use .020 thick web

(b) Vertical Stiffness -

Skin $A = .02 \times 10 = .2$ $\quad A = S\,\tau\,k$

$= 10\ (.02)\ .4$

$= .08\ in^2$

Use $\dfrac{.06 \times 1 \times 1}{(A = .12)}$ angle

(c) Caps - $A = \dfrac{m}{d\ F} = \dfrac{964 \times 15}{21 \times 30{,}000} = .023$ Since this is small use $\dfrac{.06 \times 2 \times 1 \text{ TEC}}{(A = .18\ in^2)}$

Beams 2 and 3 - These beams support the loads of O_2, H_2, H_2O and thermal capacitor. (1/2 load to each beam)

H_2 Wt. = 153 lb. ea.

O_2 Wt. = 713 lb. ea.

H_2O Wt. = 353 lb. ea.

Therm. Cap. = 250 lb. ea.

Inverter = 485 lb. ea.

Fuel Cell = 325 lb. ea.

Point Loads

(1)

$$H_2 \quad \begin{aligned} 77 \times -4.5\text{ G} &= -347\text{ lb.} \\ \frac{77 \times 9\text{ G} \times 16}{16} &= +693\text{ lb.} \\ \frac{77 \times 1.5\text{ G} \times 16}{22} &= -\ 84\text{ lb.} \\ \Sigma &= +262\text{ lb.} \end{aligned}$$

$$\text{T.C.} \quad \begin{aligned} 68 \times -4.5\text{ G} &= -306\text{ lb.} \\ \frac{68 \times 9\text{ G} \times 6}{36} &= +102\text{ lb.} \\ \frac{68 \times 1.5\text{ G} \times 6}{24} &= -\ 25\text{ lb.} \\ \Sigma &= -229\text{ lb.} \end{aligned}$$

Point (1) Total Load = + 33

(2)

$$H_2 \quad \begin{aligned} 77 \times -4.5\text{ G} &= -347\text{ lb.} \\ \frac{77 \times 9\text{ G} \times 16}{16} &= -693\text{ lb.} \\ \frac{77 \times 1.5\text{ G} \times 16}{22} &= -\ 84\text{ lb.} \end{aligned}$$

$$\text{T.C.} \quad \begin{aligned} 68 \times 4.5\text{ G} &= -306\text{ lb.} \\ \frac{68 \times 9\text{ G} \times 6}{36} &= +102\text{ lb.} \\ \frac{68 \times 1.5\text{ G} \times 6}{24} &= -\ 25\text{ lb.} \end{aligned}$$

Point (2) Total Load = - 1353 lb.

(3)

	$356 \times -4.5\text{ G}$	$= -1602$ lb.
O_2	$\frac{356 \times 9\text{ G} \times 18}{14}$	$= +4119$ lb.
	$\frac{356 \times 1.5\text{ G} \times 18}{44}$	$= -218$ lb.
	$176 \times -4.5\text{ G}$	$= -792$ lb.
H_2O	$\frac{176 \times 9\text{ G} \times 14}{37}$	$= -600$ lb.
	$\frac{176 \times 1.5\text{ G} \times 14}{24}$	$= +154$ lb.
	$82 \times -4.5\text{ G}$	$= -369$ lb.
F.C.	$\frac{82 \times 9\text{ G} \times 6}{40}$	$= +111$ lb.
	$\frac{82 \times 1.5\text{ G} \times 6}{22}$	$= -34$ lb.
	$122 \times -4.5\text{ G}$	$= -550$ lb.
	$\frac{122 \times 9\text{ G} \times 12}{40}$	$= +330$ lb.
	$\frac{122 \times 115\text{ G} \times 12}{22}$	$= -100$ lb.

Point (3) Total Load = + 449

(4)

	$356 \times -4.5\text{ G}$	$= -1602$ lb.
O_2	$\frac{356 \times 9\text{ G} \times 18}{14}$	$= -4119$ lb.
	$\frac{356 \times 1.5\text{ G} \times 18}{44}$	$= -218$ lb.
	$176 \times -4.5\text{ G}$	$= -792$ lb.
H_2O	$\frac{176 \times 9\text{ G} \times 14}{37}$	$= +600$ lb.
	$\frac{176 \times 1.5\text{ G} \times 14}{24}$	$= -154$ lb.
	$82 \times -4.5\text{ G}$	$= -369$ lb.
F.C.	$\frac{82 \times 9\text{ G} \times 6}{40}$	$= +110$ lb.
	$\frac{82 \times 1.5\text{ G} \times 6}{22}$	$= -34$ lb.
	$122 \times -4.5\text{ G}$	$= -550$ lb.
	$\frac{122 \times 9\text{ G} \times 12}{40}$	$= -330$ lb.
	$\frac{122 \times 1.5\text{ G} \times 12}{22}$	$= -100$ lb.

Point (4) Total Load = - 7558 lb.

(a) Web Thickness - Shear Load $= \frac{6011}{26} = 232$ lb/in

Skin $\tau < .020$ so use .032 thick web

(b) Vertical Stiffness -

$.03 \times 10 = .3 \quad A = S\,\tau\,K$

$= 10\,(.03)\,.4$

$= 12\text{ in}^2$

Use $\frac{.12 \times 1 \times 1}{(A = .24\text{ in}^2)}$

(c) Caps - $A = \frac{m}{d\,F} = \frac{6011 \times 16}{26 \times 30{,}000} = .123$ Use $\frac{.12 \times 2 \times 1}{(A = .36\text{ in}^2)}$ TEE

Beams 4 and 5 will carry less load than 3 and 4 so assume same material size.

Beam 6 supports loads from heaviest ends of 1, 2, 3, 4 and 5.

6011
6011
964
12986 lb. Total

$$R1 = \frac{26 \times 6011 + 50 \times 964 + 74 \times 6011}{100}$$

$$= \frac{156286 + 48200 + 444814}{100}$$

$$= \frac{649300}{100} =$$

$$R1 \text{ and } R2 = \frac{12986}{2} = 6493 \text{ lb.}$$

(a) <u>Web Thickness</u> - Shear load = $\frac{6493}{26}$ = 250 lb/in

Skin $\tau < .02$ Use <u>.040 thick web</u>

(b) <u>Vertical Stiffness</u> -

$.04 \times 10 = .4$ $A = S \tau k$

$= 10 (.04) .4$

$= .16$

Use .12 x 1 x 1 angle
($A \approx .24$ in^2)

(c) <u>Caps</u> - $A = \frac{m}{d\ F} \approx \frac{6493 \times 26}{26 \times 30{,}000} = .216$ in^2 Use .12 x 2 x 2 angle
($A \approx .48$ in^2)

<u>Beam 7</u> will carry less load than 6 so assume same material size.

<u>Check lower skin and caps as beam, with 9 G fwd load.</u>

<u>Point 1 and 3</u> (each)

O_2 = 713
H_2O = 353
F.C. = 168
Inv. = 242

1476 lb.

1476 x 9 G = 13,284 lb.

Point 2

F.C. = 325 x 9 G = 2925 lb.

(a) Web Thickness - Shear Load = $\frac{14746}{70}$ = 210 lb/in depth

Skin τ < .02   Use .04 thick web

(b) Vertical Stiffness - Same as Beam 2 and 3.

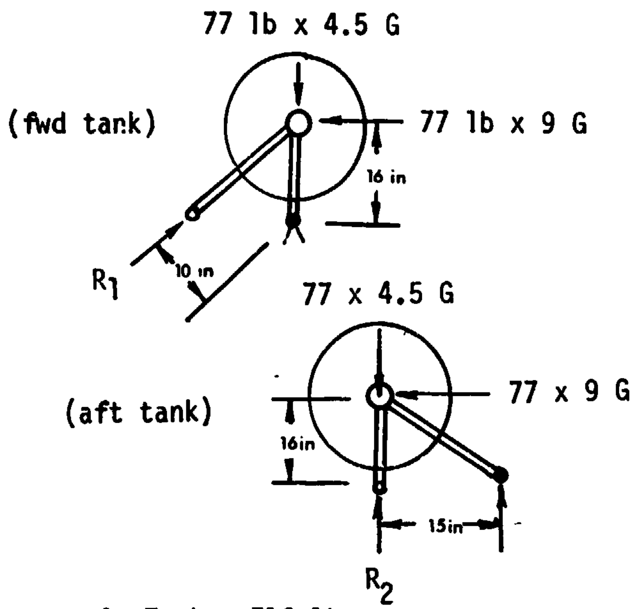
(c) Cap Area - A = $\frac{m}{d\ F}$ = $\frac{14,746 \times 26}{96 \times 30,000}$ = .133   Use .12 x 2 x 2 angle

(A ≈ .48 in^2)

TANK SUPPORT STRUCTURAL SIZING

H_2 Tank - 53 lb.

77 lb/side



R1 = $\frac{77 \times 9 \times 16}{10}$ = 1108 lb. load

Length = 30"

From curves use   O.D. x .   Wall

R2 = (77 x 4.5) + $\frac{(77 \times 9 \times 16)}{15}$

= 347 + 739

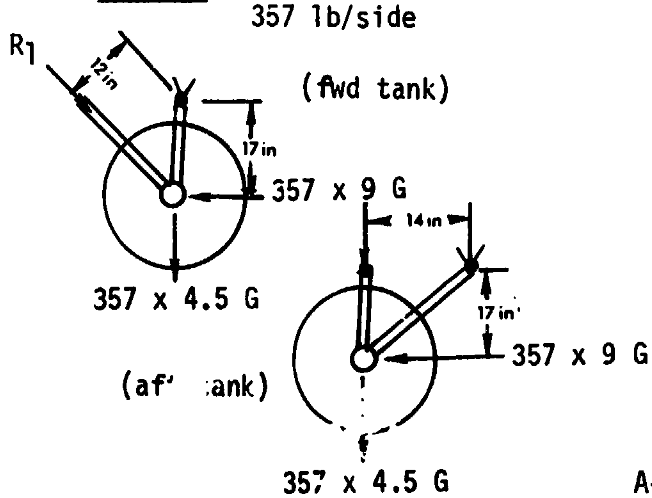
= 1085 lb. load

Length = 15"

From curves use   O.D. x .   Wall

O_2 Tank - 713 lb.

357 lb/side



R1 = $\frac{357 \times 9 \times 17}{12}$ = 4551 lb. load

Length = 22"

From curves use   O.D. x .   Wall

R2 = $\frac{(357 \times 9\ G \times 16) - (357 \times 4.5\ G \times 14)}{14}$

= $\frac{51408 - 23491}{14}$

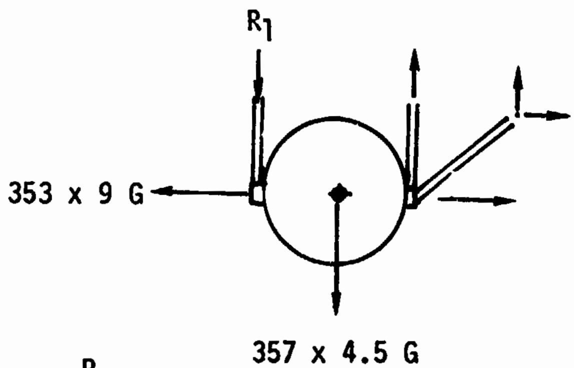
= $\frac{28917}{14}$ = 2065 lb. load

Length = 1

From curves use   O.D. x .   Wall

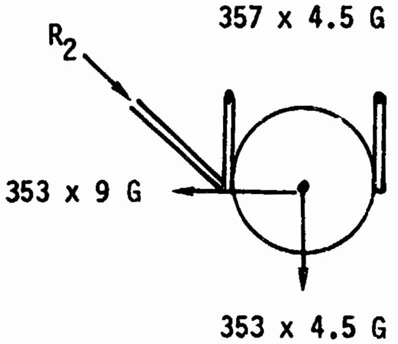
H_2O Tank - 353 lb.

177 lb/side



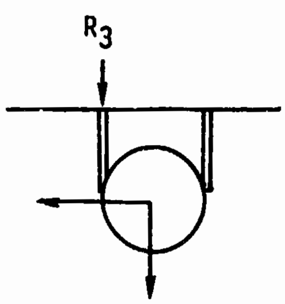
$$R1 = \frac{(357 \times 4.5 \times 35) - (357 \times 9 \times 14)}{54}$$

$$\frac{56229 - 44987}{54} = 208 \text{ lb.}$$



$$R2 = \frac{10 \times 353 \times 5}{28} = 630 \text{ lb.}$$

Worst Case Tube



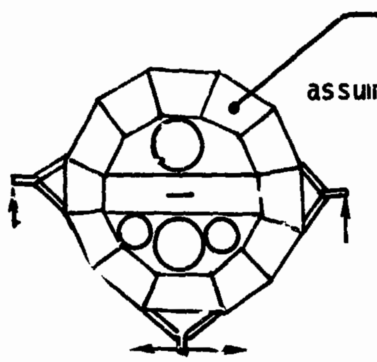
R3 = (357 x 9 [illegible] 357 x 4.5 x 19)

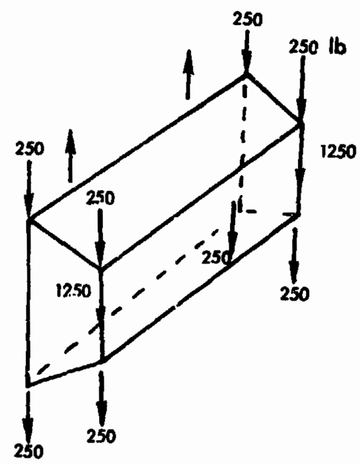
= (44932 - 3[illegible]) / 37

$$= \frac{14459}{37} = 390 \text{ lb.}$$

PAYLOAD STRUCTURE SIZING

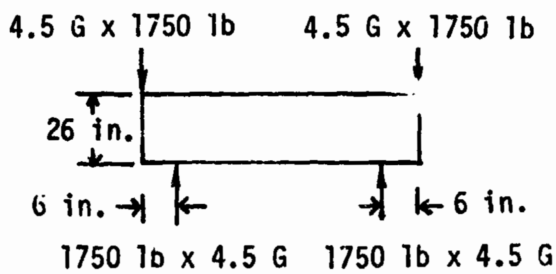
Exp.	3450 lb.
Ht/Power	5000 lb.
Str.	1000 lb.





$$\begin{array}{r} 1250 \\ 500 \\ \hline 1750 \end{array}$$

inboard panel



(a) Web - Shear load = $\frac{1750 \times 4.5}{26}$ = 303 lb/in Skin - ≈ .020

Use <u>.030 thick web</u>

(b) Stiffener Area -

A = 10 x .03 = .3

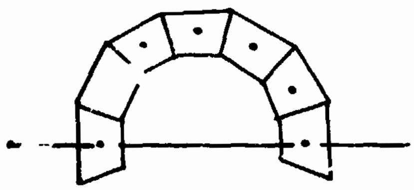
A = S K = .12

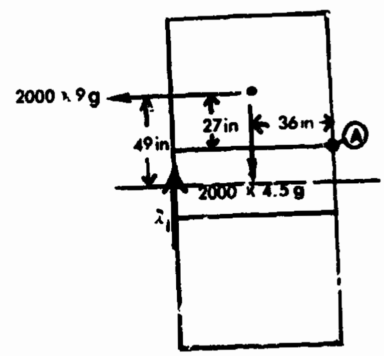
= 10 (.03) .4

(b) <u>Stiffener Area</u> (Cont.) -

Use .12 x 1 x 1 angle

(c) <u>Caps</u> - $A = \frac{m}{d\ F} = \frac{1750 \times 4.5 \times 6}{26 \times 30{,}000} = .06$ Use .12 x 1.5 x 1.5 angle





$$L = \frac{400 \times 65 + 800 \times 57 + 800 \times 32.5}{2000}$$

$$L = \frac{26000 + 45600 + 26000}{2000}$$

$$L = \frac{97600}{2000}$$

$$L = 48.8$$

$$R1 = \frac{2000 \times 4.5\ G \times 36 + 2000 \times 9\ G \times 27}{72}$$

$$= \frac{324000 + 486000}{72}$$

$$= \frac{810{,}000}{72}$$

$$= 11250 \text{ lb.}$$

$\div\ 4 = 2812$ lb.

1.5 x 1.5 x .08 Min

WEIGHTS - POWER/HEAT REJECTION MODULE STRUCTURE

Comp.	Item	Size	(Sz.x .1) Wt.	Qty.	Item Tot. Wt.	(1ea.req.) Comp. Tot. Wt.
Beam 1	Web Vert. Stif. Caps	.02 x 27 x 72 .06 x 2 x 27 .06 x 3 x 72	3.88 .32 1.30	1 7 2	3.88 2.27 2.60	8.75
Beam 2	Web Vert. Stif. Caps	.032 x 27 x 72 .12 x 2 x 27 .12 x 3 x 72	6.22 .65 2.60	1 10 2	6.22 6.5 5.18	17.90
Beam 3		Same as Beam 2				17.90
Beam 4	Web Vert. Stif. Caps	.032 x 27 x 72 .12 x 2 x 27 .18 x 4 x 72	6.22 .65 5.18	1 12 2	6.22 7.78 10.36	24.36
Beam 5		Same as Beam 4				24.36
Beam 6	Web Vert. Stif. Caps	.04 x 27 x 100 .12 x 2 x 27 .18 x 4 x 100	10.80 .65 7.2	1 12 2	10.80 7.78 14.40	32.98
Beam 7		Same as Beam 6				32.98
Top Panel	Skin Lat. Stif. Long. Stif.	.04 x 72 x 100 .12 x 2 x 100 .12 x 2 x 72	28.8 2.4 1.73	1 3 4	28.80 7.20 6.91	42.91
Bottom Panel		Same as Top Panel				42.91
H_2 Tank (2 reqd.)	Vert. Strut. Fwd. Strut. Side Strut.	1x.035|.128x$\frac{15}{12}$ 1x.035|.128x$\frac{20}{12}$ 1x.035|.128x$\frac{30}{12}$	.16 .21 .32	4 4 2	.64 .84 .64	2.12
O_2 Tank (2 reqd.)	Vert. Strut. Fwd. Strut. Side Strut.	1.5x.035|.193x$\frac{18}{12}$ 1.5x.035|.193x$\frac{22}{12}$ 1.5x.035|.193x$\frac{34}{12}$	.29 .35 .55	4 4 2	1.16 1.42 1.10	3.68
H_2O (2 reqd.)	Vert. Strut. Fwd. Strut. Side Strut.	1x.035|.128x$\frac{18}{22}$ 1x.035|.128x$\frac{24}{12}$ 1x.035|.128x$\frac{26}{12}$	.2 .26 .28	4 2 4	.40 .52 1.12	2.04

Add 10% for fittings - 280 lb. TOTAL Module Structure Weight 253 lb.

WEIGHTS - EXPERIMENT STRUCTURE

Comp.	Item	Size	Wt.	(Size x.1) Qty.	Item Tot. Wt.	
Common Payload Cell	Inboard Skin	.025x27x72	4.86	1	4.86	
	Outboard Skin	.032x42x72	9.68	1	9.68	
	Side Skin	.020x31x72	4.5	2	9.00	
	End Skins	.032x30 35	3.36	2	6.72	
	Intermed. Frame Webs	.020x30x35	2.1	3	6.30	
	Longerons	.100x3x72	2.16	4	8.64	
	End Frame Caps	.125x3x134	5.03	2	10.06	
	Intermed. Frame Caps	.06x3x134	2.41	3	7.24	
	Intermed. Long Stif.	.06x2x72	.86	4	3.46	
	Intermed. Sta. Stif.	.06x2x134	1.61	4	6.43	
						72.4 lb/cell 72.4x9=652 lb (6')
	Correction for 7' long $(72.4 + \frac{72.4}{6} = 72.4 + 12.1 =$ 84.5 lb/cell for 7' long) 9 x 84.5 = 760.5 lb					
Structural Payload Cell	Inboard Skin	.032x27x72	6.22	1	6.22	
	Outboard Skin	.032x47x72	9.67	1	9.67	
	Side Skin	.032x31x72	7.14	2	14.28	
	End & Intermed. Skins	.032x30x35	3.36	4	13.44	
	Longerons	.188x3x72	4.06	4	16.24	
	End Frame Caps	.188x3x134	7.56	2	15.12	
	Intermed. Frm. Caps	.125x3x134	5.06	2	10.05	
	Long. Stiffeners	.09x2x72	1.3	4	5.18	
	Station Stiffeners	.09x2x134	2.41	2	4.82	
						95 lb/cell 95x3=285 (6')
	Correction for 7' long $(95 + \frac{95}{6} = 95 + 15.8 =$ 110.8 lb/cell for 7' long) 3 x 110.8 = 332.4 lb					937 lb Total (6') 1093 lb Total (7')

Add 10% for fittings

1200 lb TOTAL

Payload Structure

7' Long